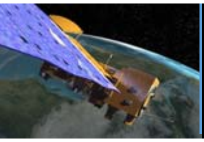
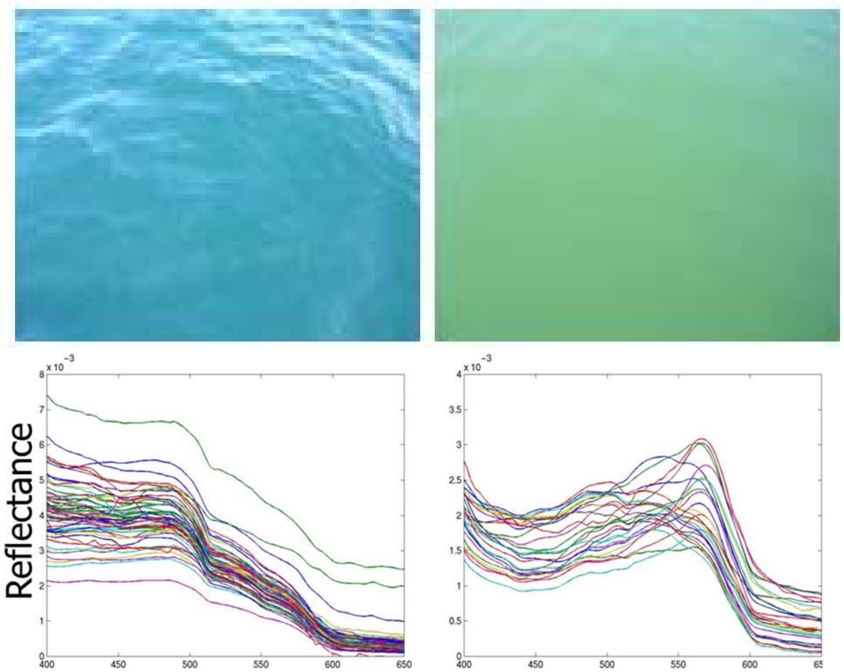
Building Toward a New Lidar Era in Satellite Oceanography

Michael Behrenfeld
Oregon State University



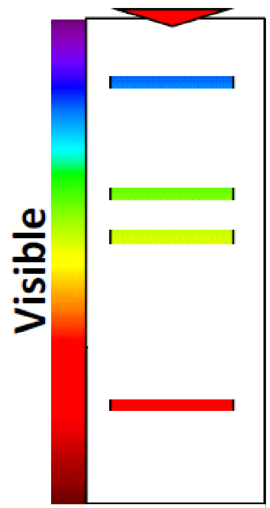
Traditional Satellite Ocean Color Measurements

'*Ocean Color*' is the measurement of *solar reflectance spectra*



Low phytoplankton ("blue" water)

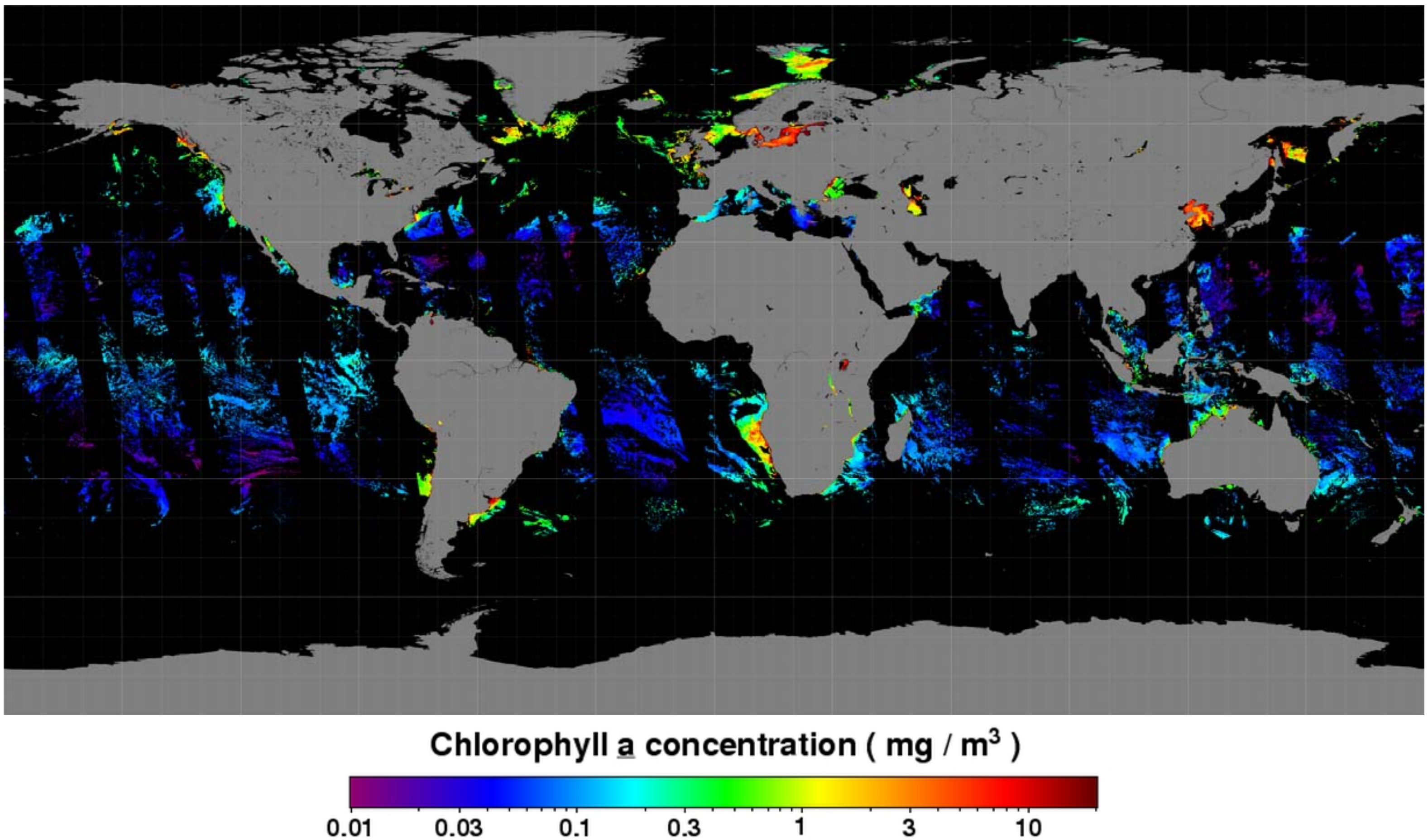
High phytoplankton ("green" water)



Coastal Zone Color Scanner (CZCS)

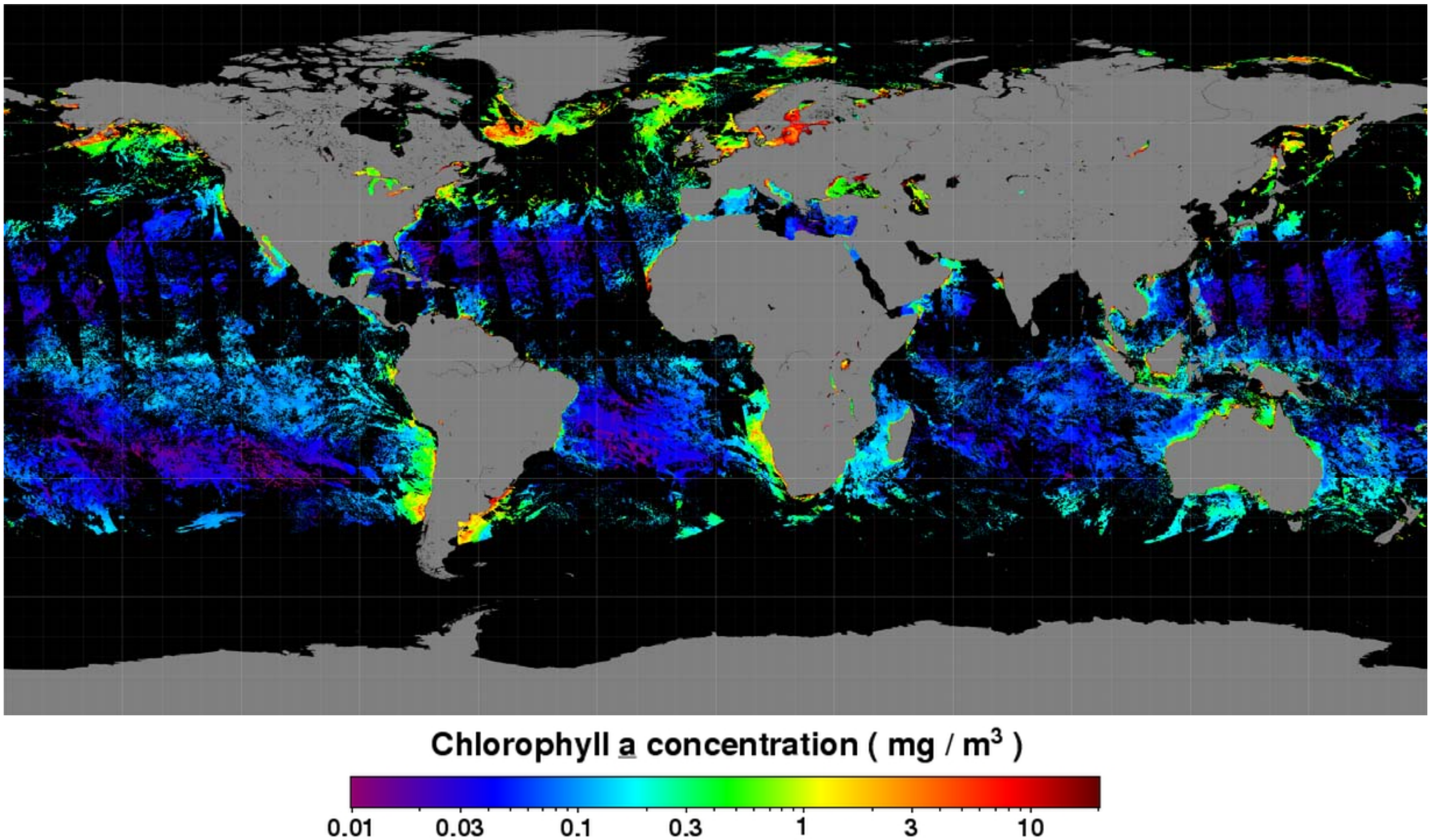
Traditional Satellite Ocean Color Measurements

Daily composite: MODIS Aqua



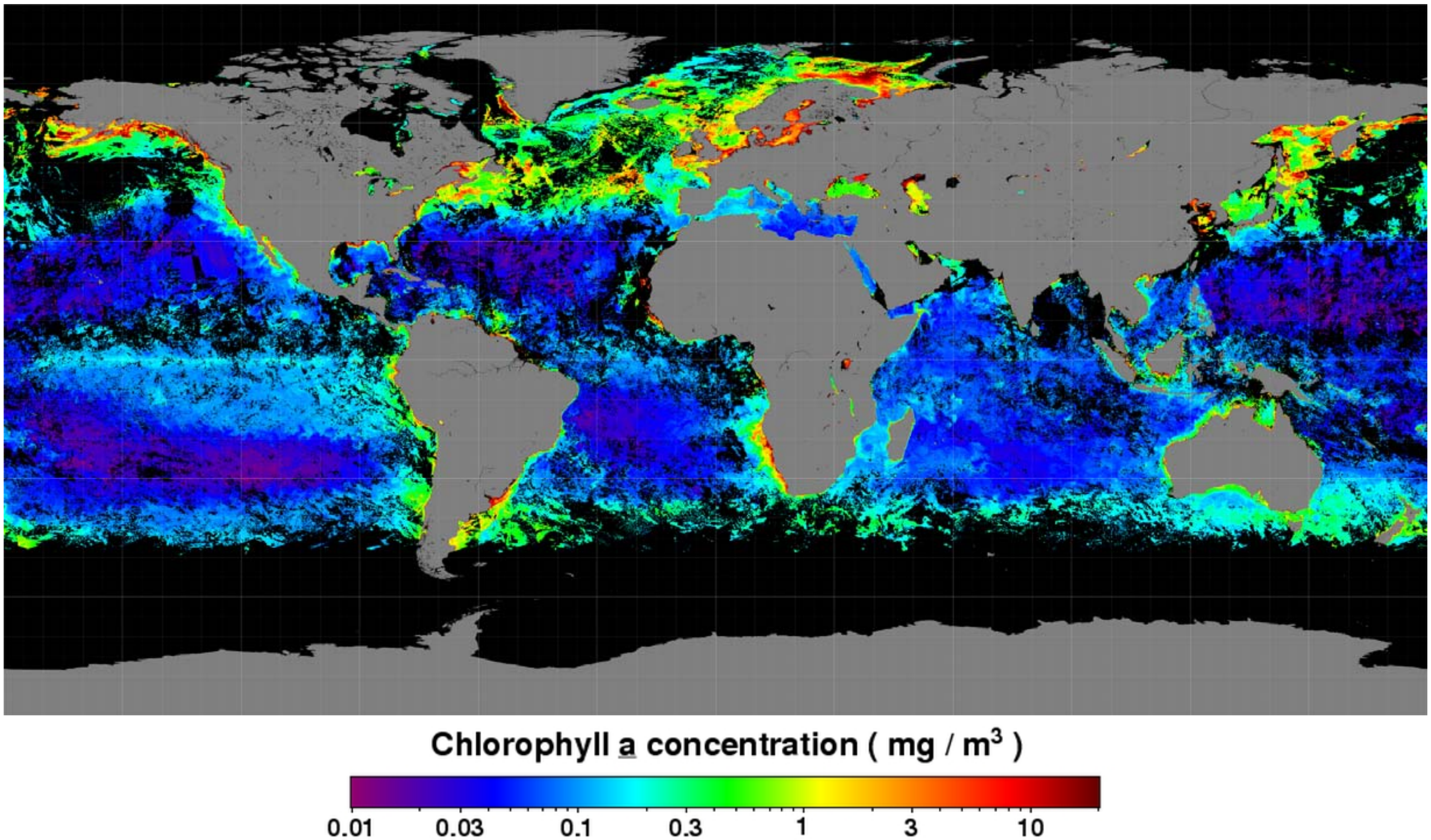
Traditional Satellite Ocean Color Measurements

3-Day composite



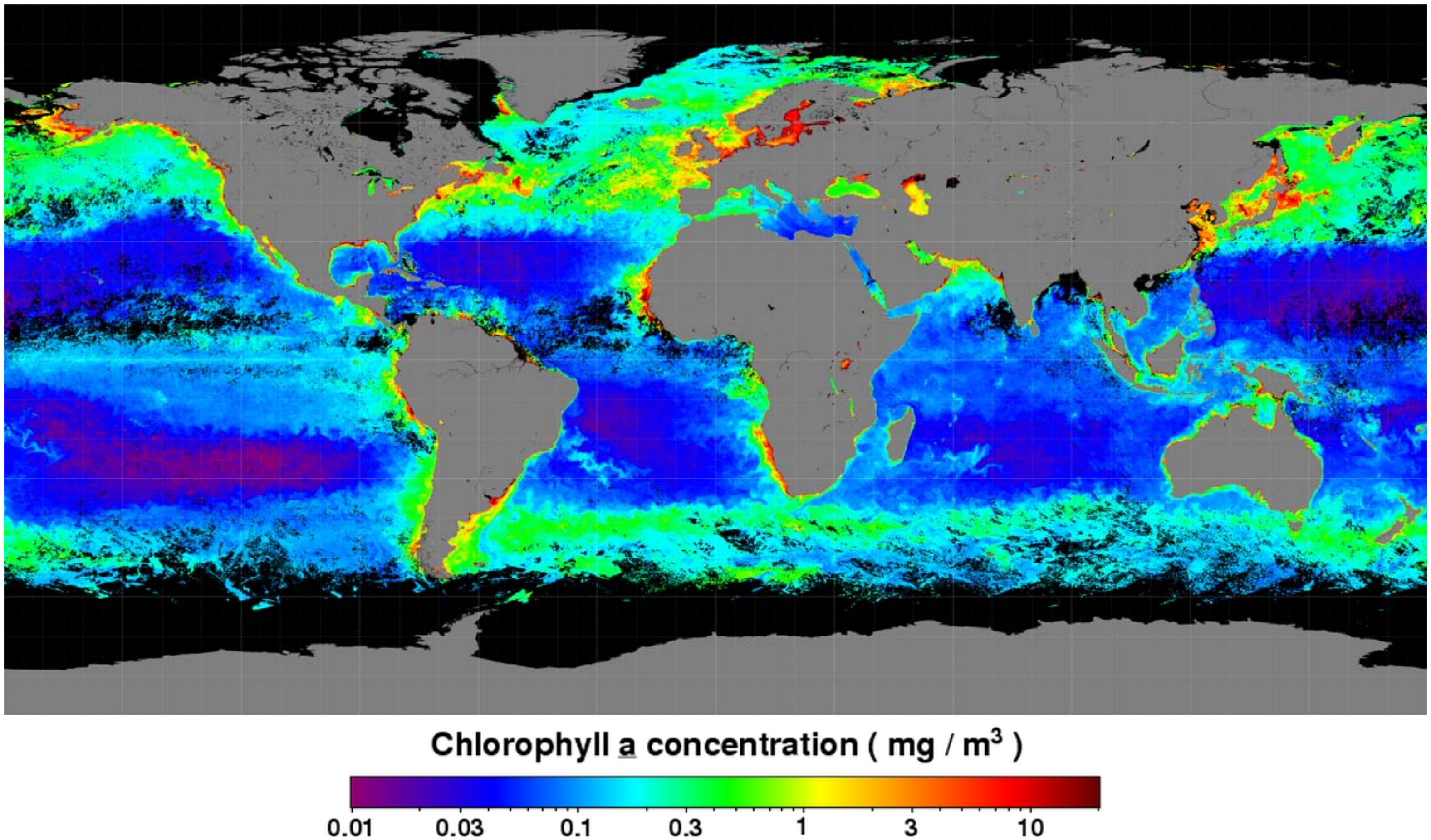
Traditional Satellite Ocean Color Measurements

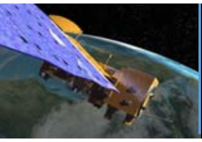
8-Day composite



Traditional Satellite Ocean Color Measurements

Monthly composite

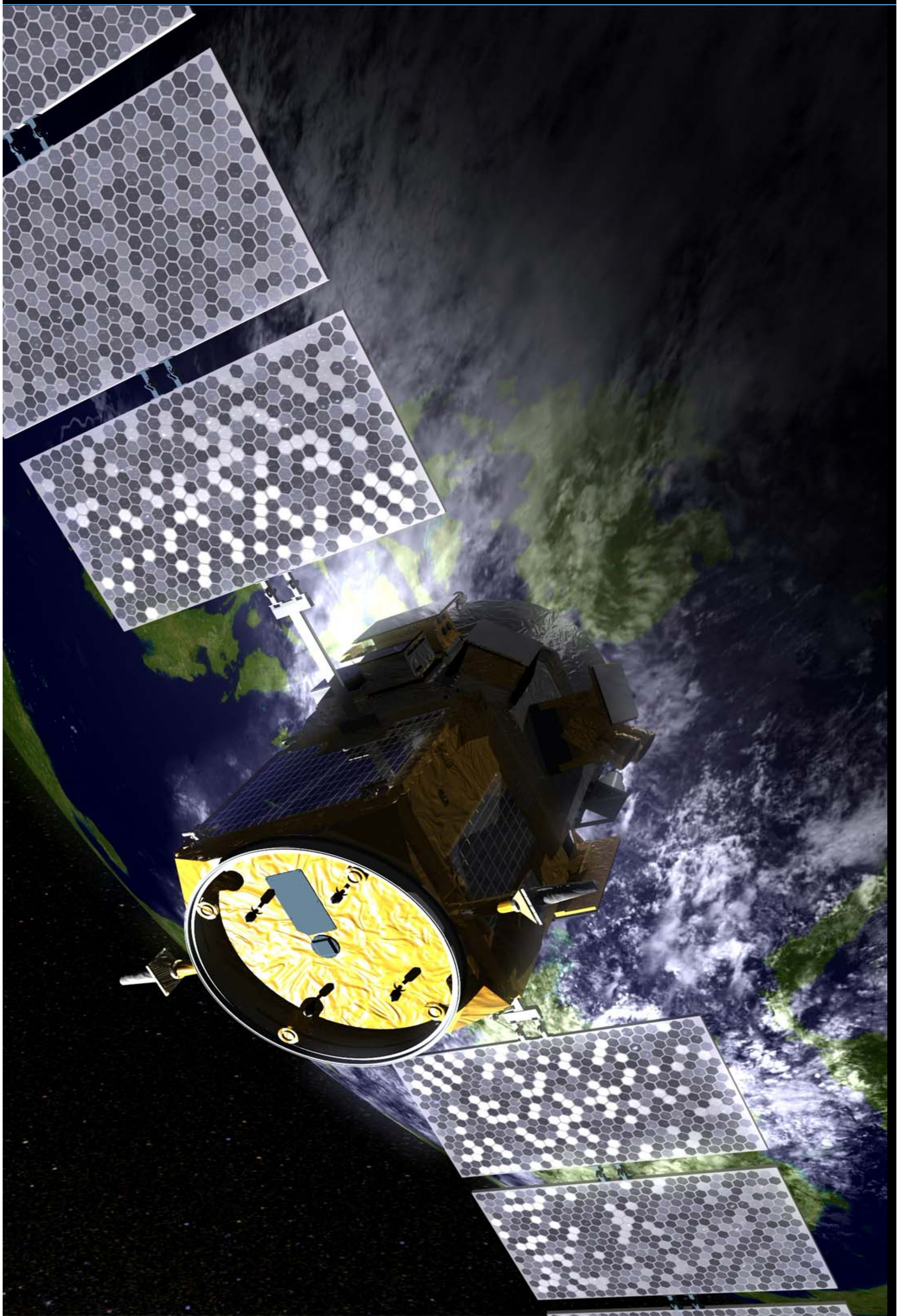




Challenges

- atmospheric contributions dominate the measured top-of-atmosphere signal and accurate corrections are challenging
- ocean component of the signal is primarily only from the upper ½ optical depth
- approach provides no direct information on vertical distributions of ocean constituents
- the retrieved ocean property (water leaving reflectance) is an optically integrated property without a direct signal for separating absorption and scattering fractions
- global sampling is compromised by aerosols, clouds, and solar angle ◀ particularly problematic at high latitudes during winter months
- no information is available on plankton properties during the night

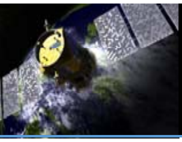
Lidar & Oceanography



Active Lidar Measurements

Lidar (Light Detection And Ranging)

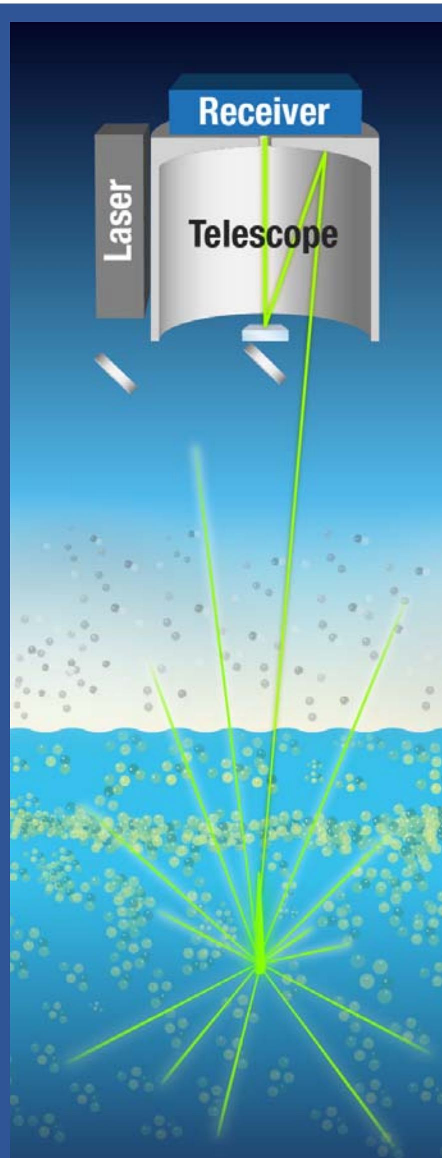
- signal from a known source (laser)
- constant viewing geometry
- minimal atmosphere correction issues
- can penetrate deep into photic layer
- resolves vertical structure
- retrievals through aerosols/thin clouds & between clouds
- day and night sampling

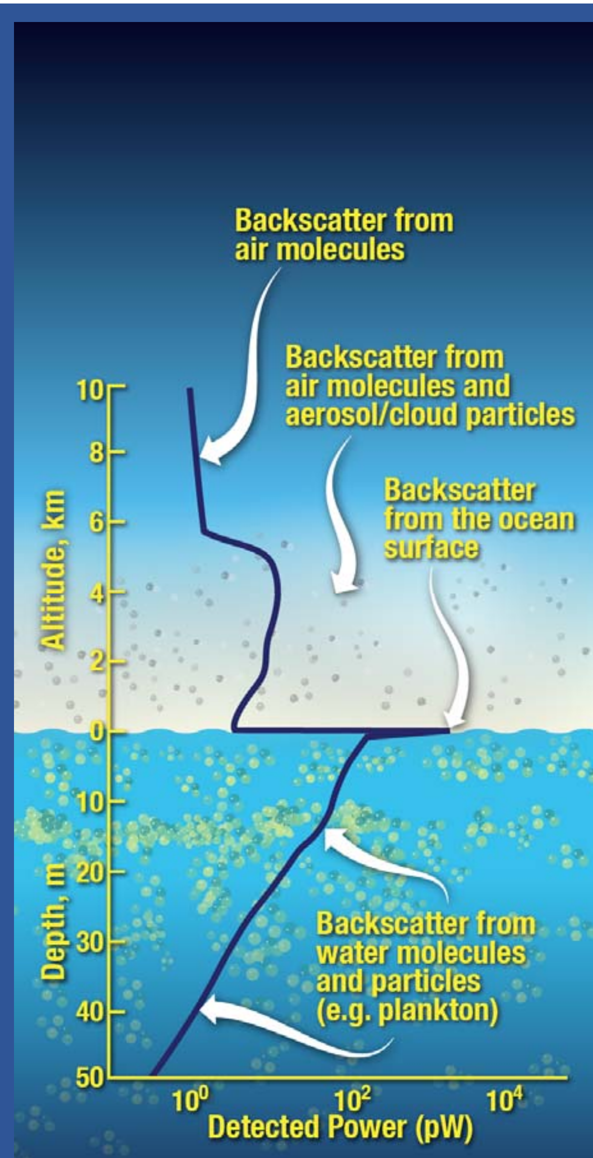


Storyboard:

1. How does it work?
2. Notes from the field
3. Going to space
4. Little bit o' science
5. Thinking forward

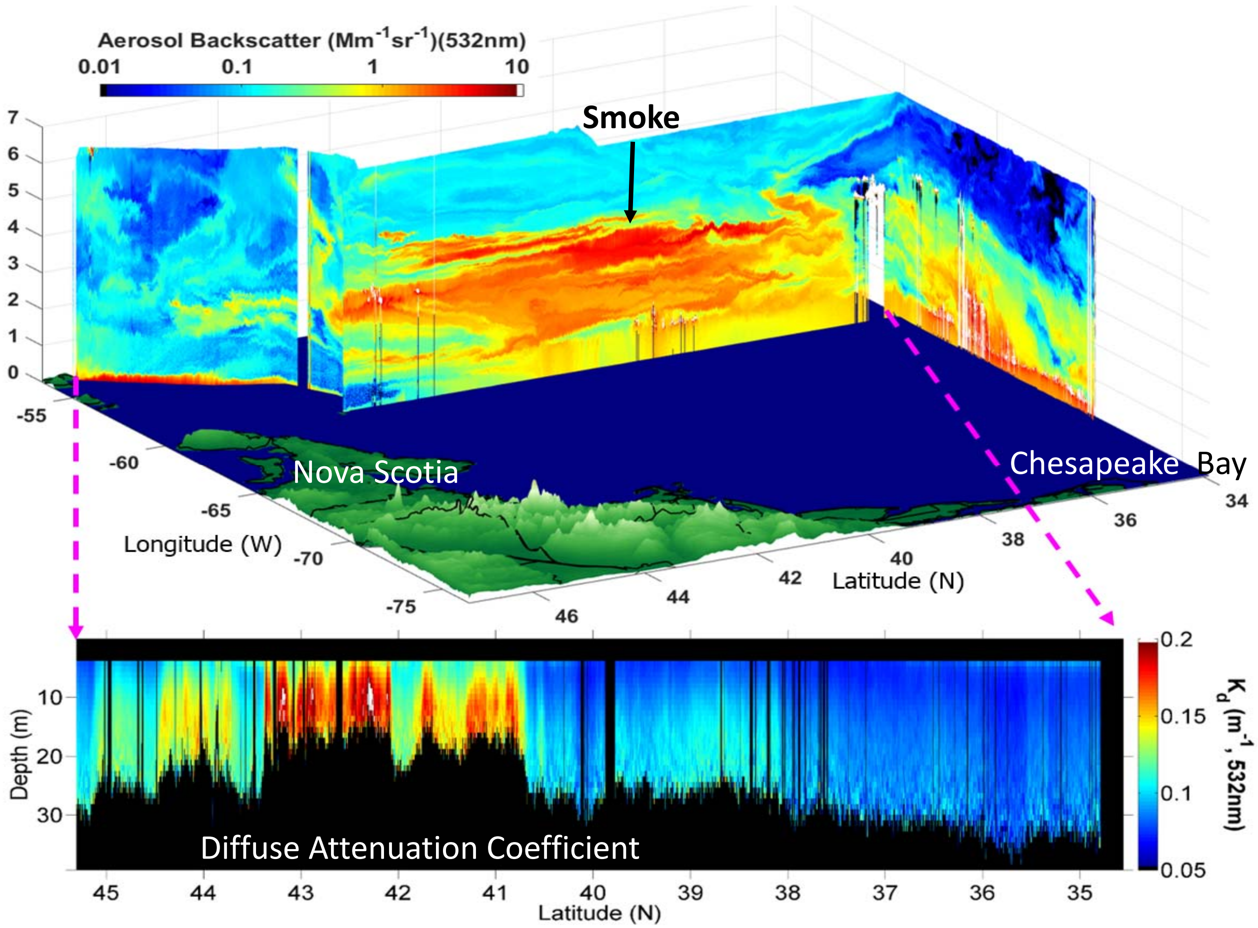
Lidar 101: How does it work?





Active Lidar Measurements

The Lidar ‘Curtain’



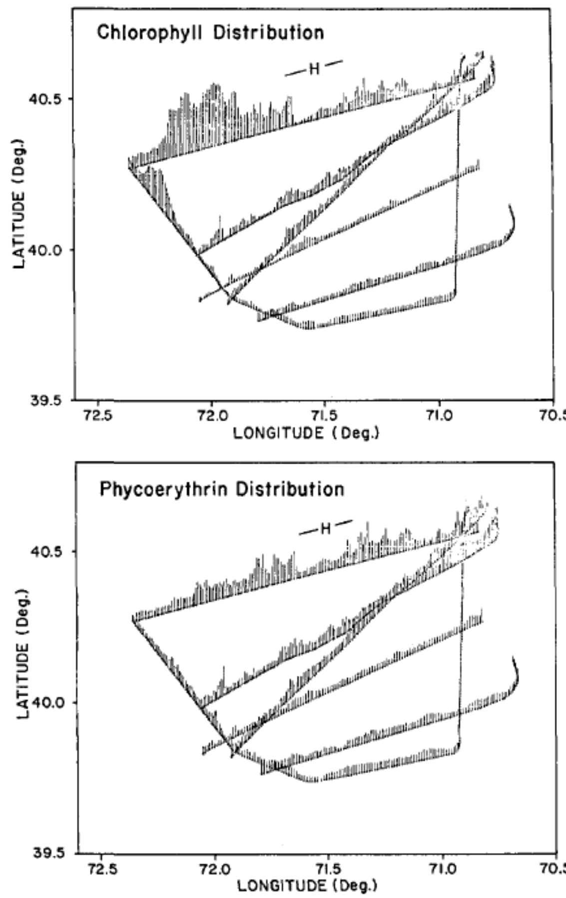
* note, these data are from an advanced airborne lidar system (discussed later)

Notes from the field: Airborne lidar

Active Lidar Measurements

Early Airborne Measurements

- Kim et al. 1973: Chlorophyll fluorescence
- Bristow et al. 1981, Hoge et al. 1981, 1986: Raman to quantify chlorophyll & phycoerythrin
- Billard et al. 1986, Hoge et al. 1988, Smart & Kwon 1996, Bunkin & Surovegin 1992: Early profiling of (relative) backscattering attenuation
- Hoge et al. 1993, 1995: 355 nm for CDOM
- Yoder et al. 1993: Chlorophyll spatial variability during JGOFS North Atlantic Bloom Experiment
- Martin et al. 1994: Chlorophyll fluorescence to map iron stress response during IronExI

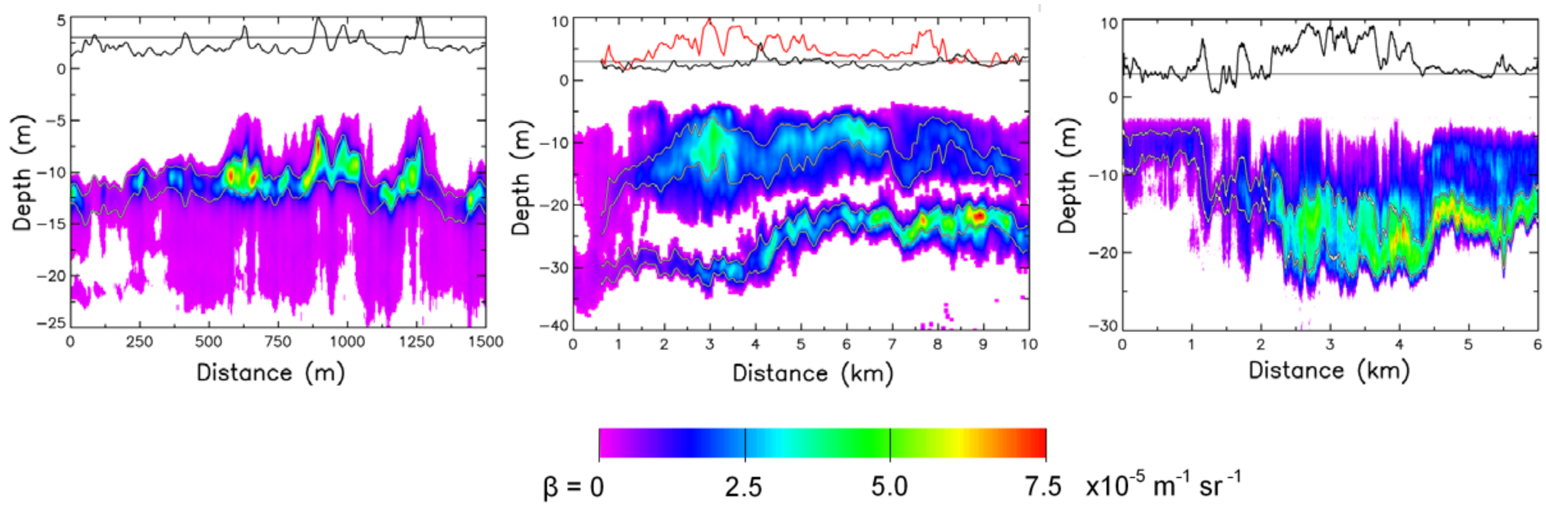


From: Hoge et al. 1986

Active Lidar Measurements

Airborne LiDAR profiling
– Jim Churnside –

- Churnside et al. 1991, 2001, 2003: Detect/quantify fish schools
- Churnside & Ostrovsky 2005, Churnside & Donaghay 2009: Detect plankton layers
- Churnside 2015: Profiles of attenuation, backscatter, & chlorophyll
- Churnside 2016: Vertical distribution of net primary productivity



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The beam attenuation to chlorophyll ratio: an optical index of phytoplankton physiology in the surface ocean?

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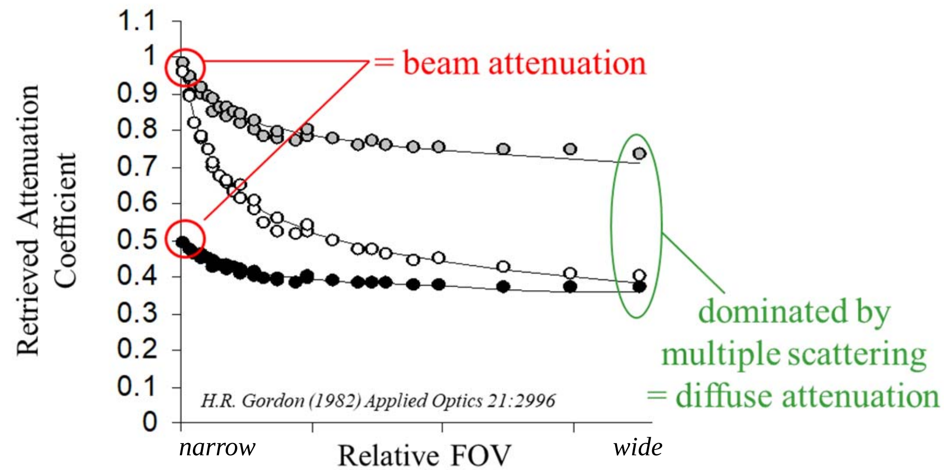
Abstract

The particulate beam attenuation coefficient (c_p) is proportional to the concentration of suspended particles in a size domain overlapping that of the phytoplankton assemblage. c_p is largely insensitive to changes in intracellular chlorophyll concentration, which varies with growth irradiance (a process termed 'photoacclimation'). Earlier studies have shown that the ratio of c_p:chlorophyll (i.e., c_p^*) exhibits depth-dependent changes that are consistent with photoacclimation. Similar relationships may likewise be expected in the horizontal and temporal dimensions, reflecting changes in mixing depth, incident irradiance, and light attenuation. A link between c_p^* and more robust photoadaptive variables has never been explicitly tested in the field. Here we use five historical field data sets to directly compare spatial and temporal variability in c_p^* with two independent indices of photoacclimation: the light-saturated, chlorophyll-normalized photosynthetic rate, P^b_{opt}, and the light-saturation index, E_k. For the variety of oceanographic conditions considered, a first-order correlation emerged between c_p^* and P^b_{opt} or E_k. These simple empirical results suggest that a relationship exists between a bio-optical variable that can potentially be retrieved remotely (c_p^*) and physiological variables crucial for estimating primary productivity in the sea.



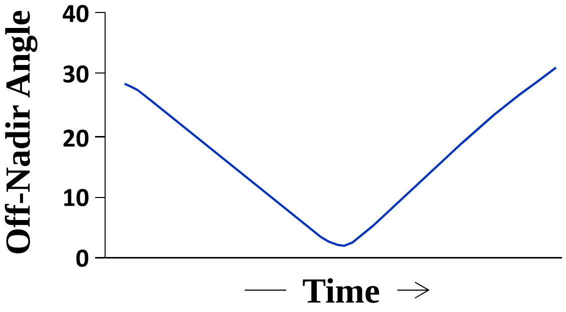
…are there any existing data indicating plankton retrievals are possible with a space-based lidar?

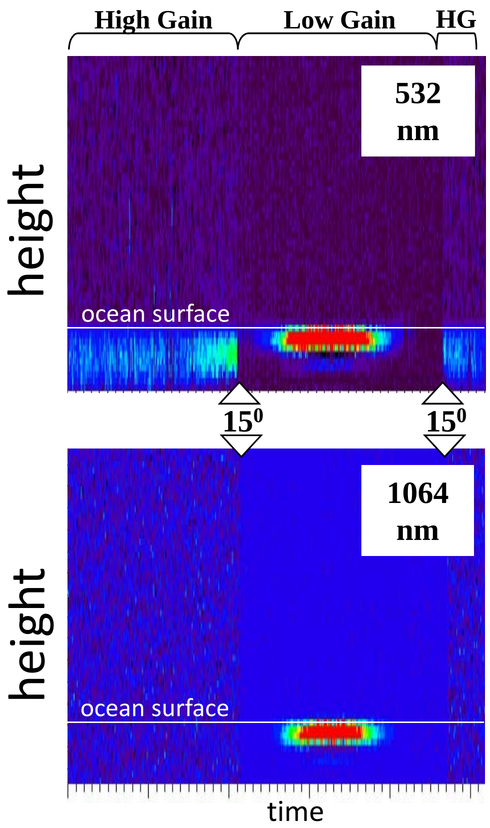
Going to Space

Active Lidar Measurements

Lidar In-space Technology Experiment (LITE)

- Discovery Space Shuttle in September 1994
- 3-wavelength Nd-Yg lidar
- 1064 = 486 mJ; 532 = 460 mJ; 355 = 196 mJ
- Multi-angle (+/-30^0) maneuvers over Lake Superior and Gulf of California



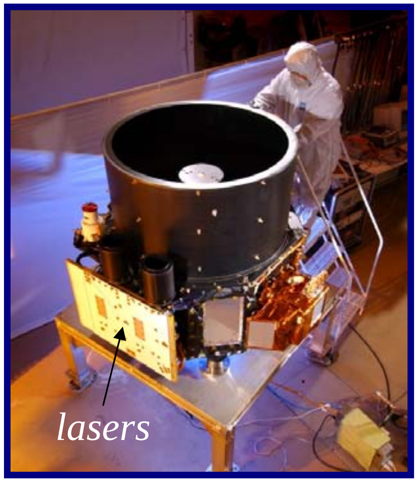


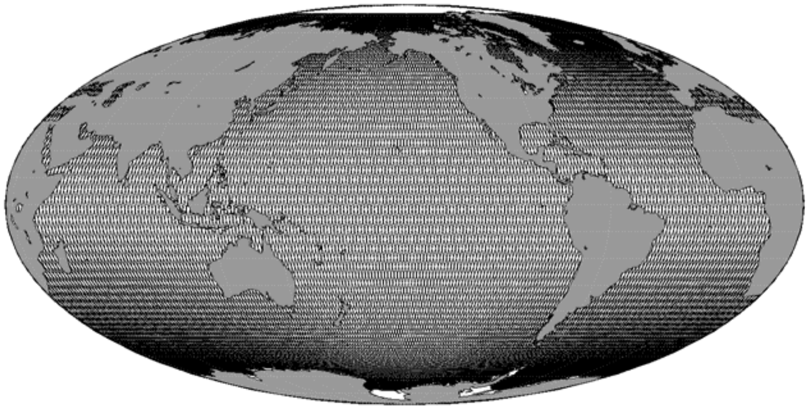
two important things happened next…

Active Lidar Measurements

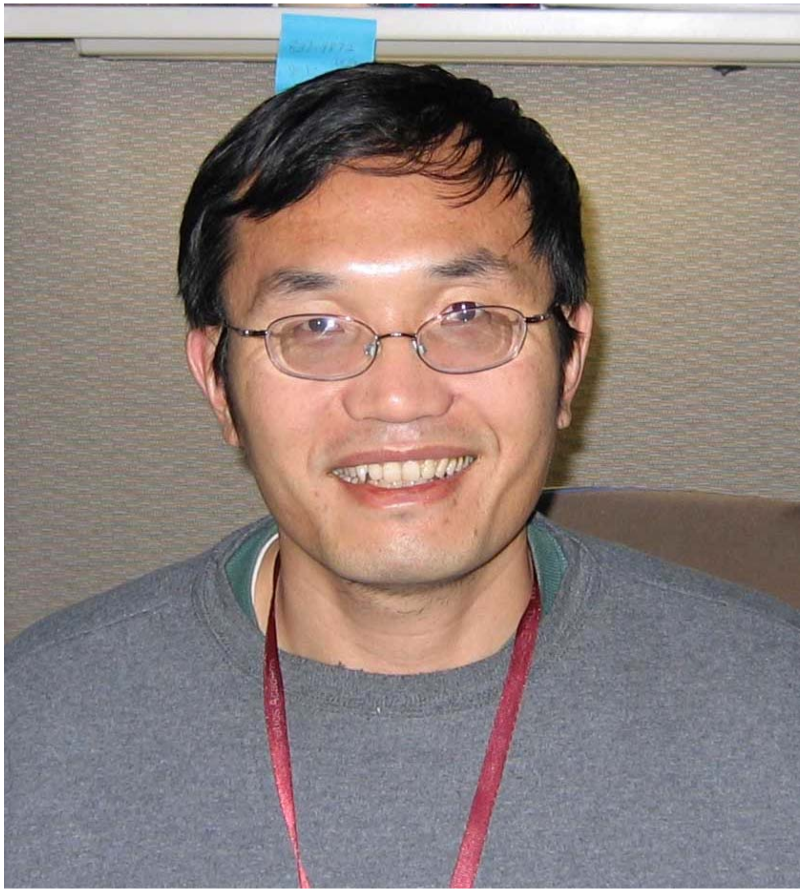
#1. Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)

- NASA-CNES partnership
- launched April 28, 2006, still active
- definitively **NOT** designed for ocean applications
- 2-wavelength 110 mJ Nd:Yg laser (532, 1064 nm)
- 3-channel ($532\parallel$, $532\perp$, 1064 nm)
- 1 meter telescope
- 100 m footprint
- 30 m air / 23 m water vertical resolution
- polar orbiting, 16 day repeat cycle ↵



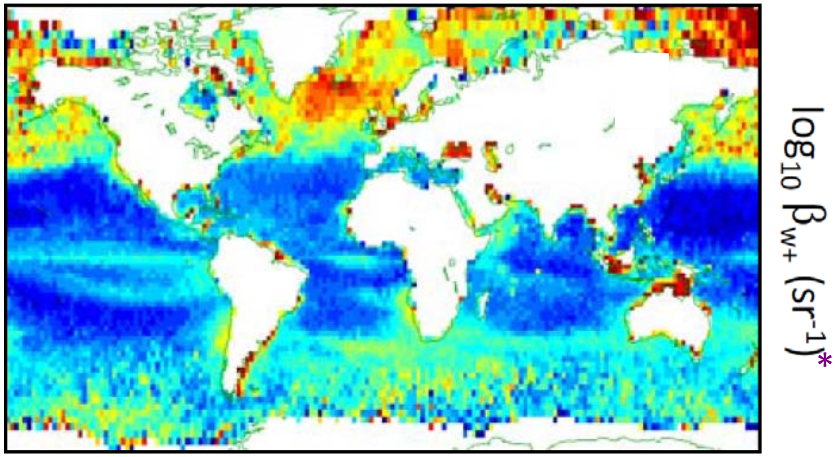


Active Lidar Measurements

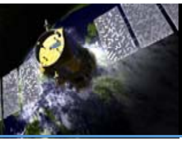


#2. Yongxiang 'Yong' Hu

The first global ocean property retrieved with a satellite lidar as presented during the 2007 Ocean Color Research Team Meeting

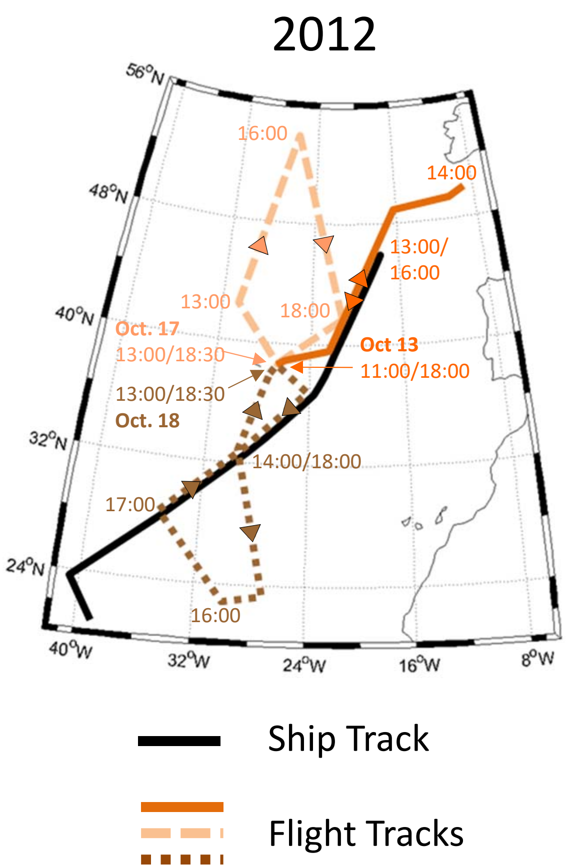


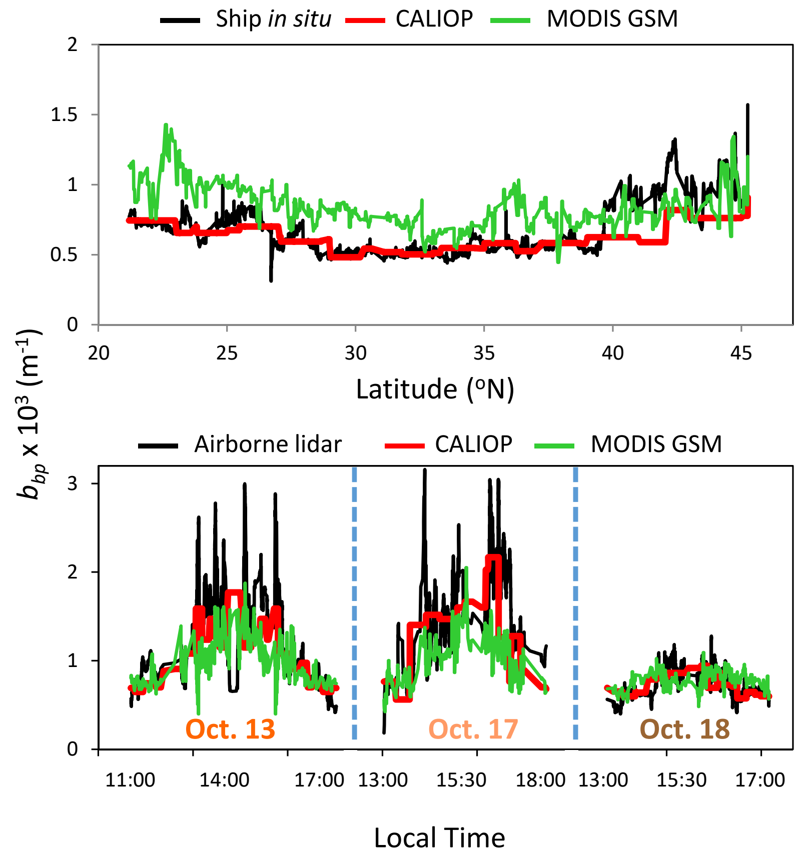
* β_{W+} = column integrated cross polarized ocean lidar backscatter



Active Lidar Measurements

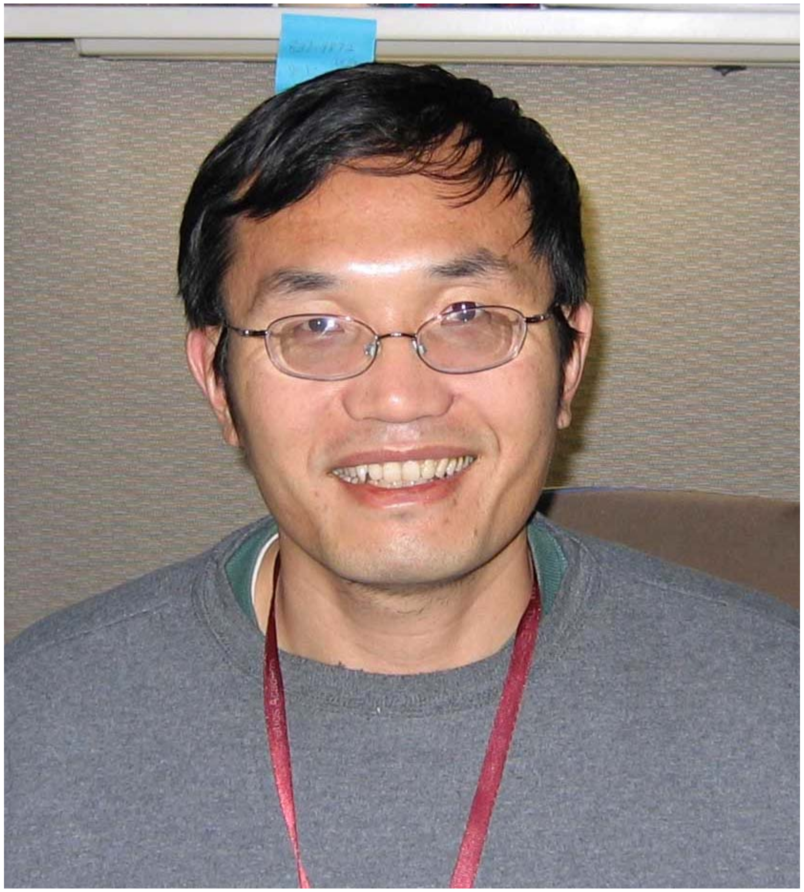
Field-testing Retrievals





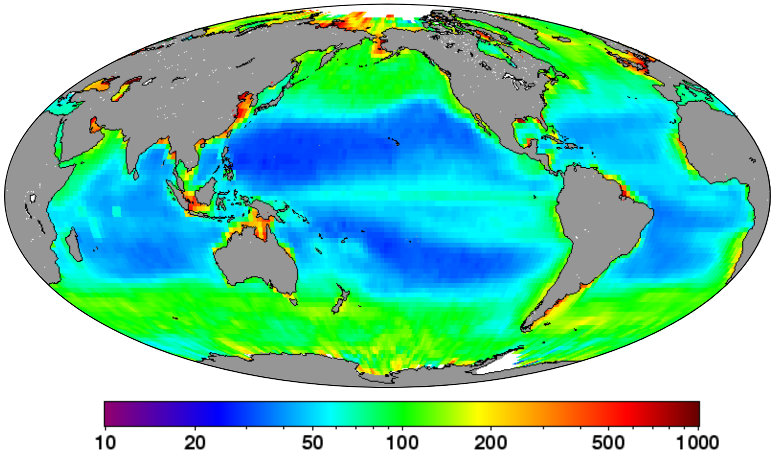
Behrenfeld et al. 2013 Geophys. Res. Lett. 40, 4355-4360

Active Lidar Measurements



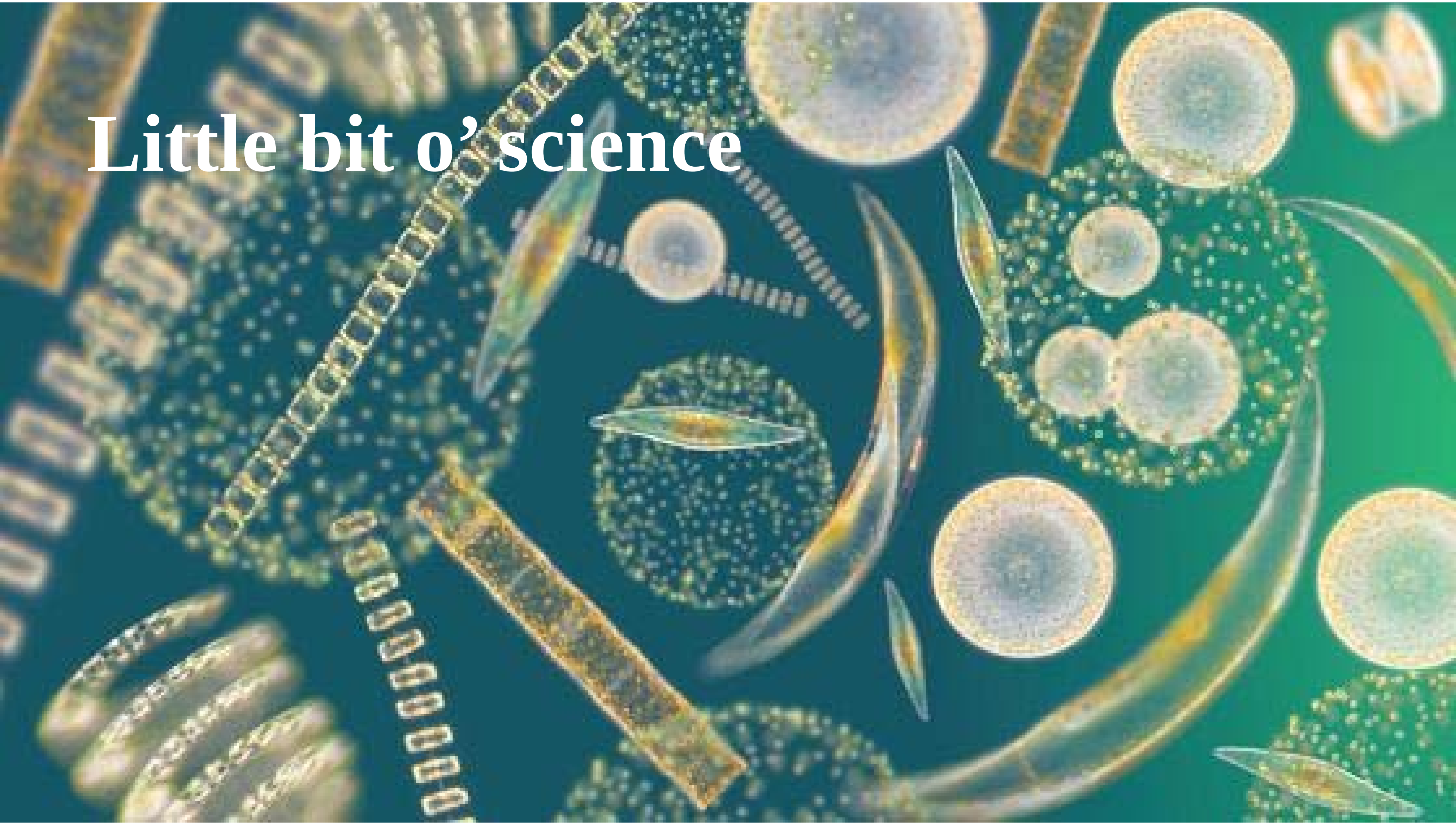
#2. Yongxiang 'Yong' Hu

Space-based lidar measurements of global ocean carbon stocks



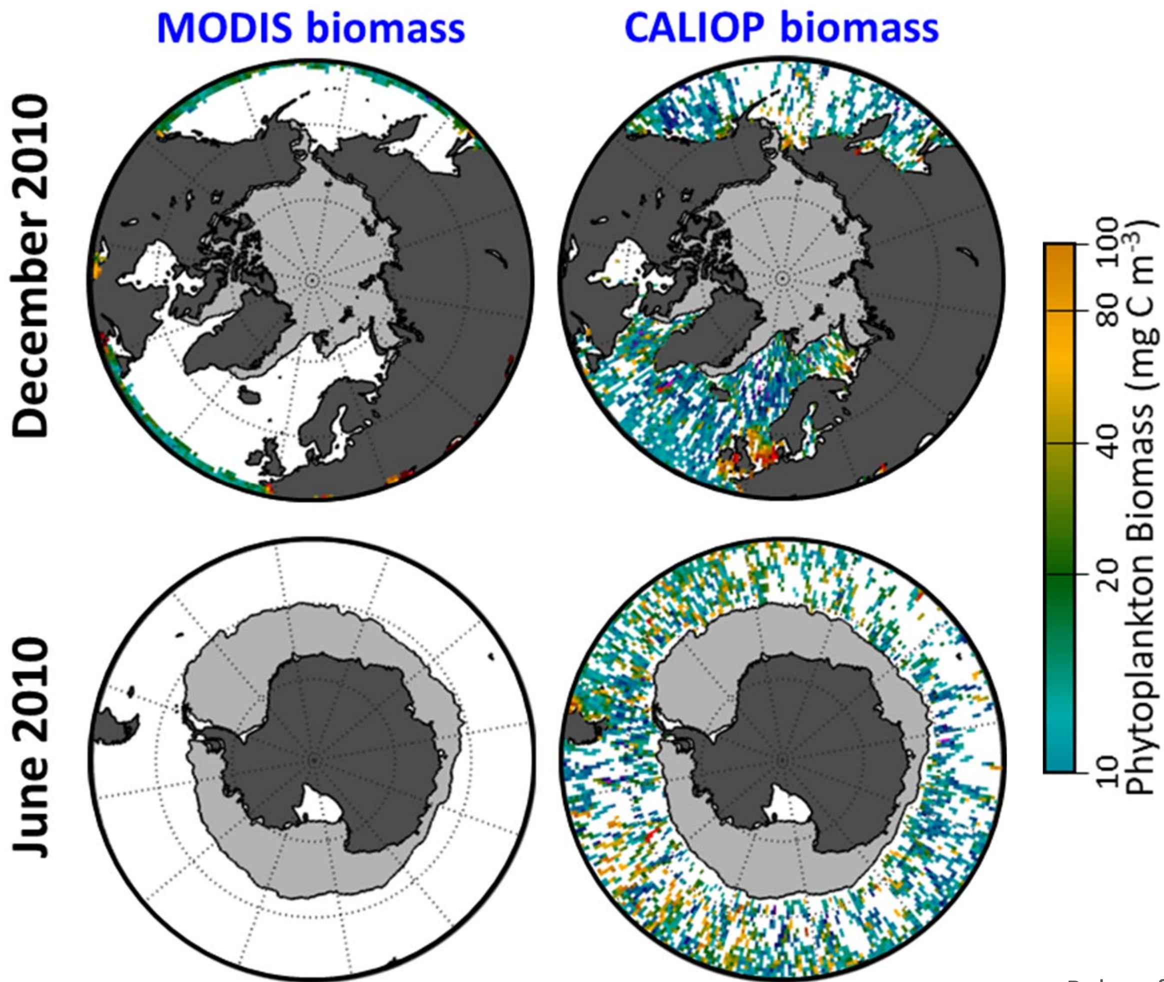
Behrenfeld et al. 2013 Geophys. Res. Lett. 40, 4355-4360

Little bit o' science



Active Lidar Measurements

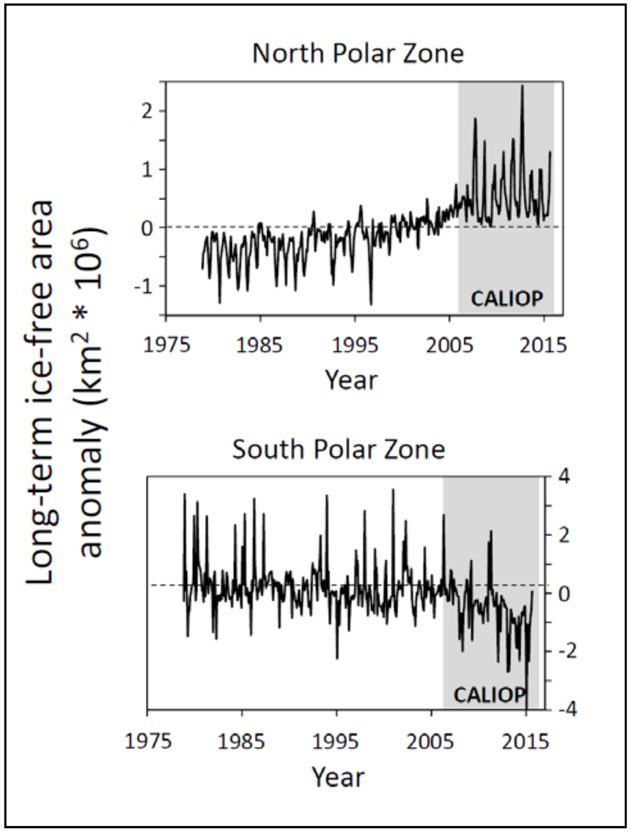
CALIOP Shines on Polar Ecosystems

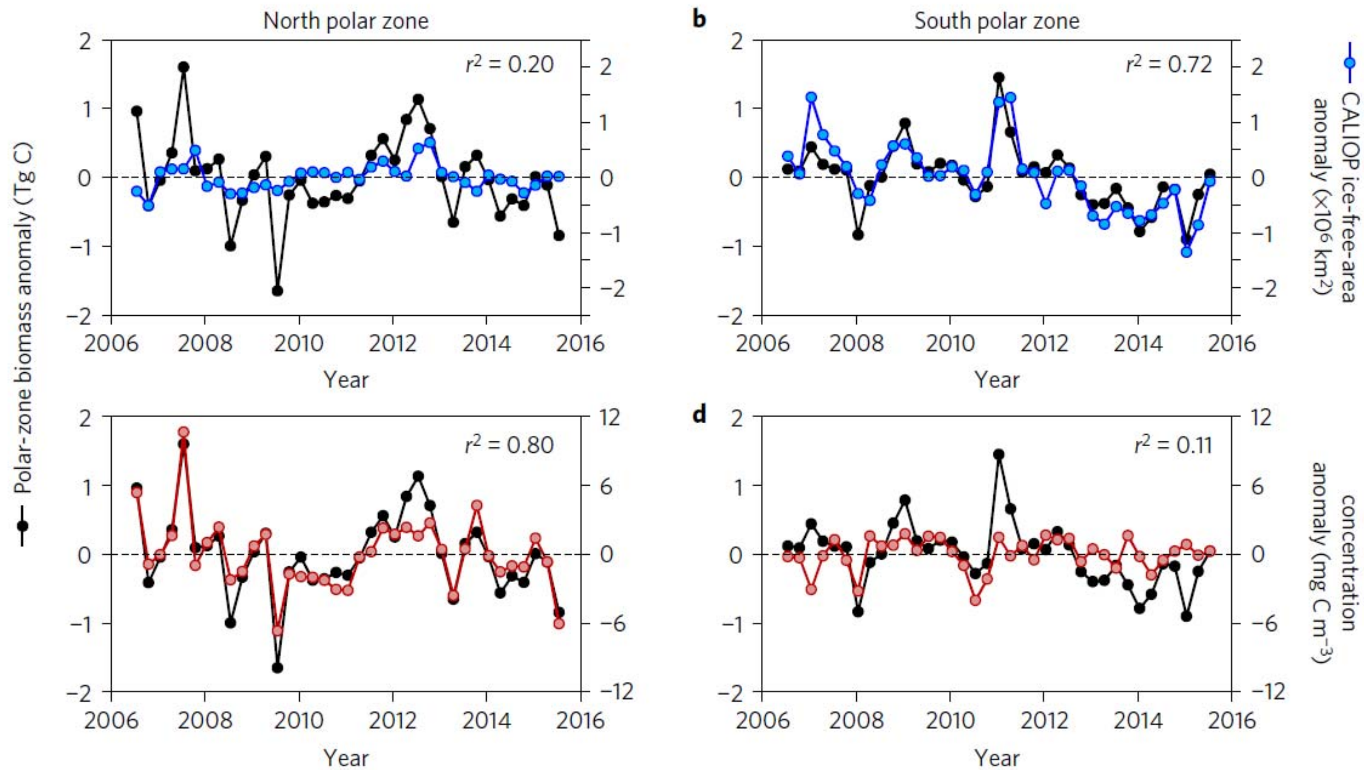


…let's look first simply at long term trends in polar-zone-integrated phytoplankton biomass…

Behrenfeld et al. 2016 Nature Geoscience 19, 118-122

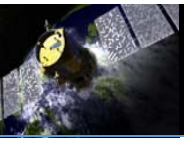
Active Lidar Measurements





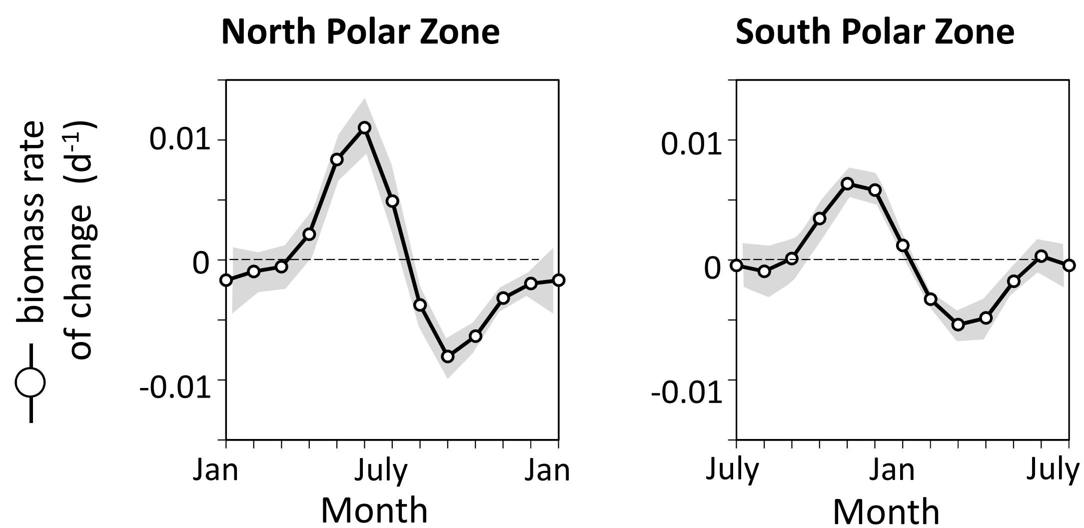
…now, let's use the complete annual cycle coverage provided by CALIOP to look at bloom dynamics…

Behrenfeld et al. 2016 Nature Geoscience 19, 118-122

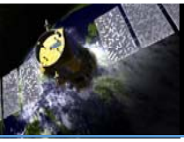


Active Lidar Measurements

Polar Biomass Dynamics

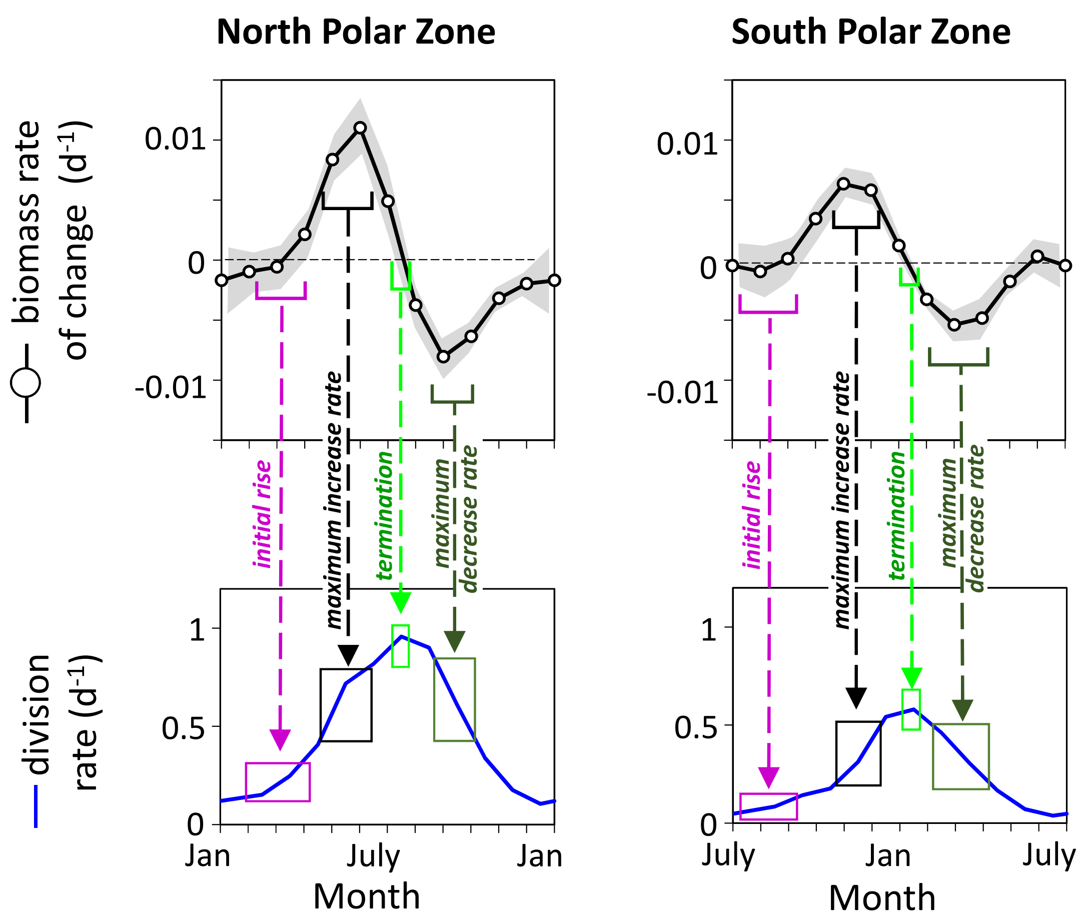


Behrenfeld et al. 2016 Nature Geoscience 19, 118-122



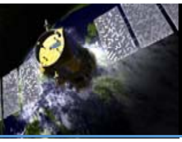
Active Lidar Measurements

Polar Biomass Dynamics



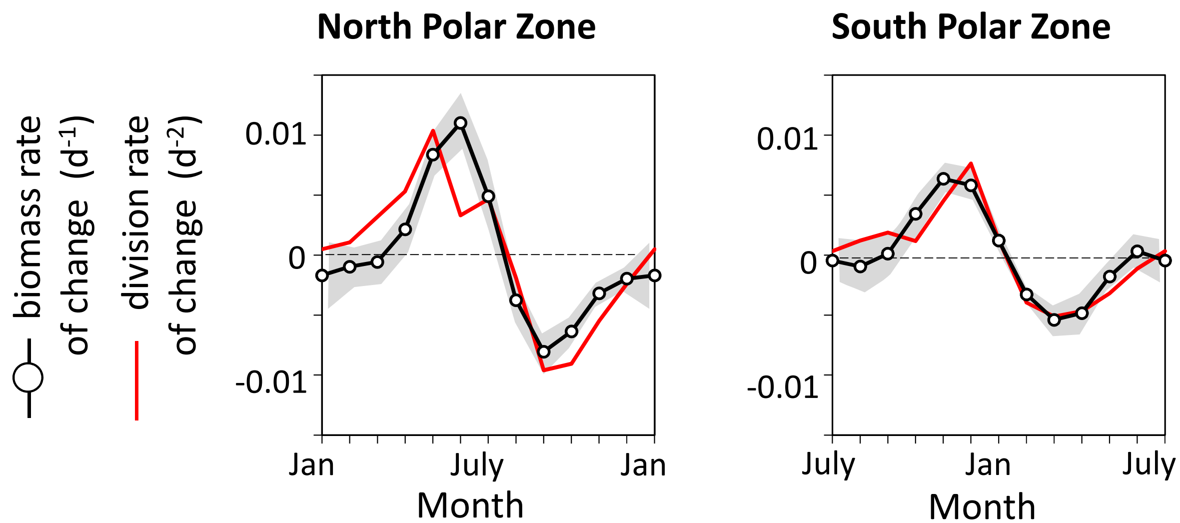
Now, envision the derivative of these annual cycles…

Behrenfeld et al. 2016 Nature Geoscience 19, 118-122



Active Lidar Measurements

Polar Biomass Dynamics

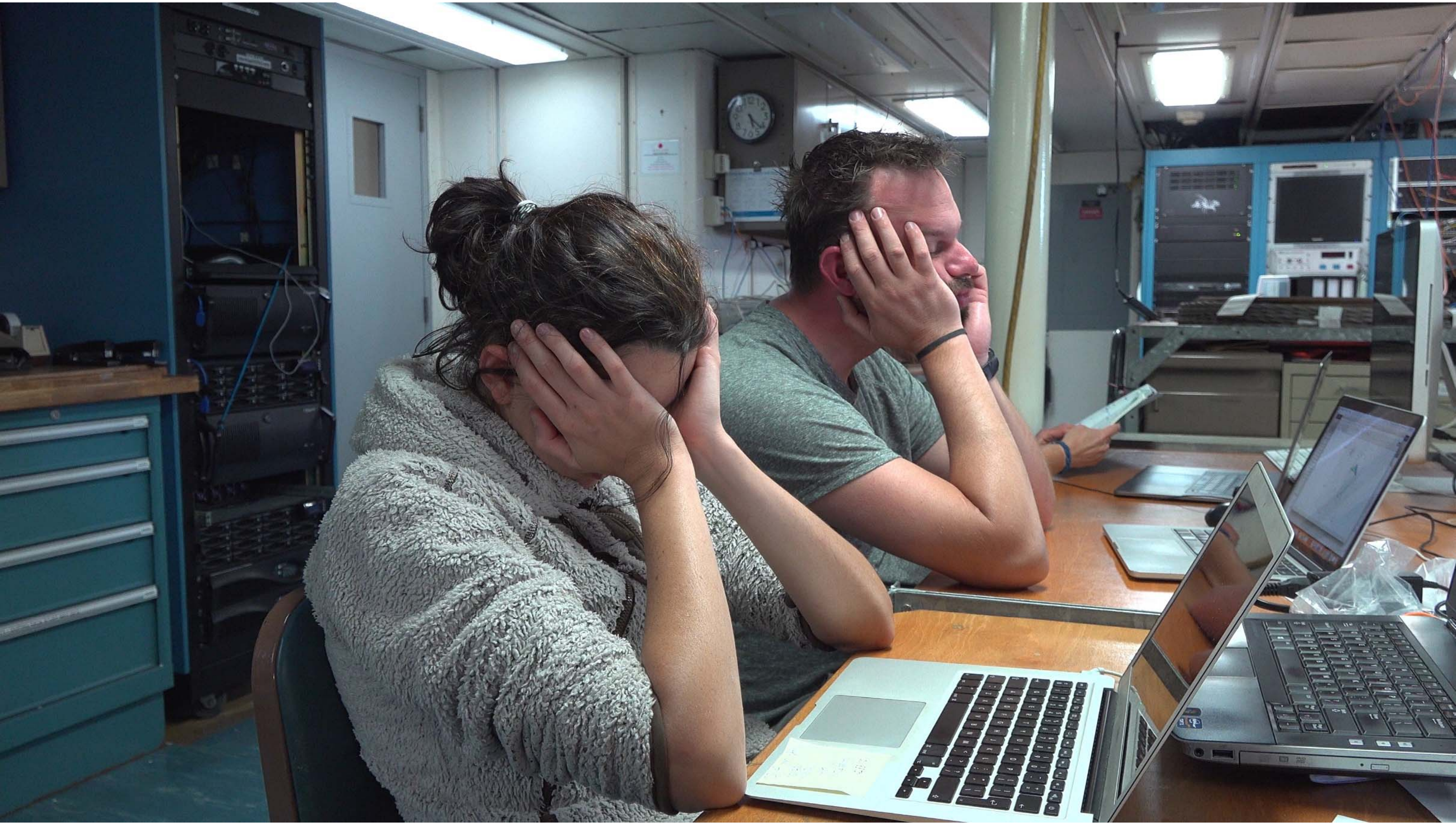


Conclusion: The annual cycle in biomass is driven by accelerations and decelerations in phytoplankton division rates because division and loss rates are always tightly coupled but with a short temporal lag in predation (zooplankton, viruses, etc)

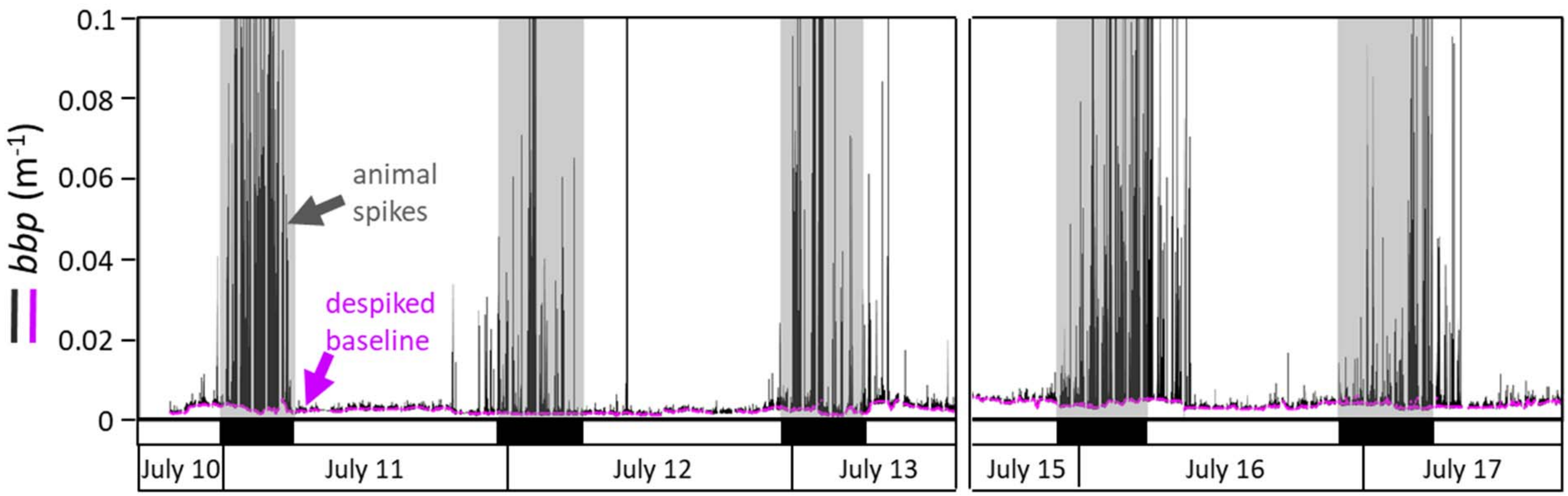
Behrenfeld et al. 2016 Nature Geoscience 19, 118-122

‘DVM’

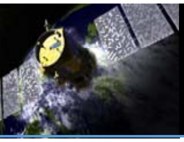
Diel Vertical Migration



Active Lidar Measurements

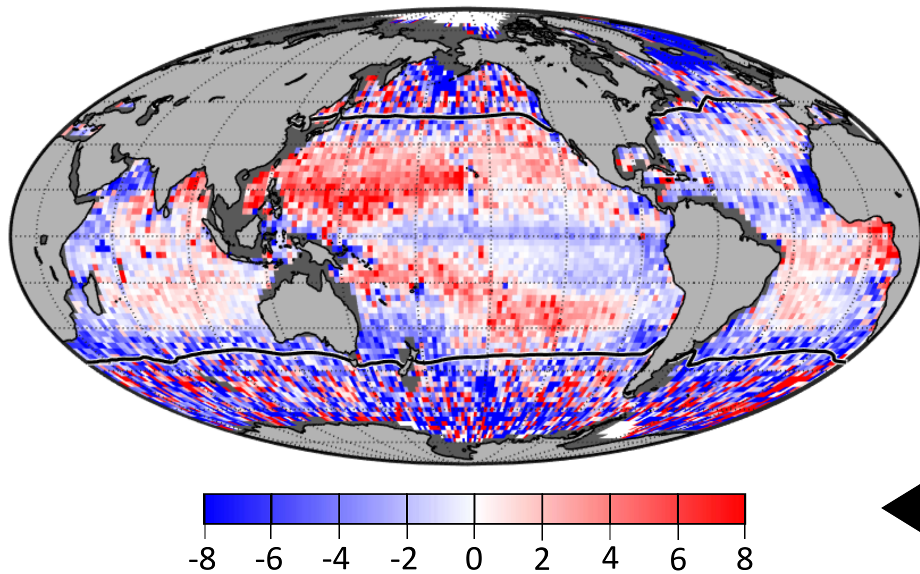


Burt W. J. & Tortell, P. D. 2018. *Geophys, Res. Lett. 45*. doi.org/10.1029/2018GL079992



Active Lidar Measurements

The fundamental CALIOP retrieval



Why are there negatives?

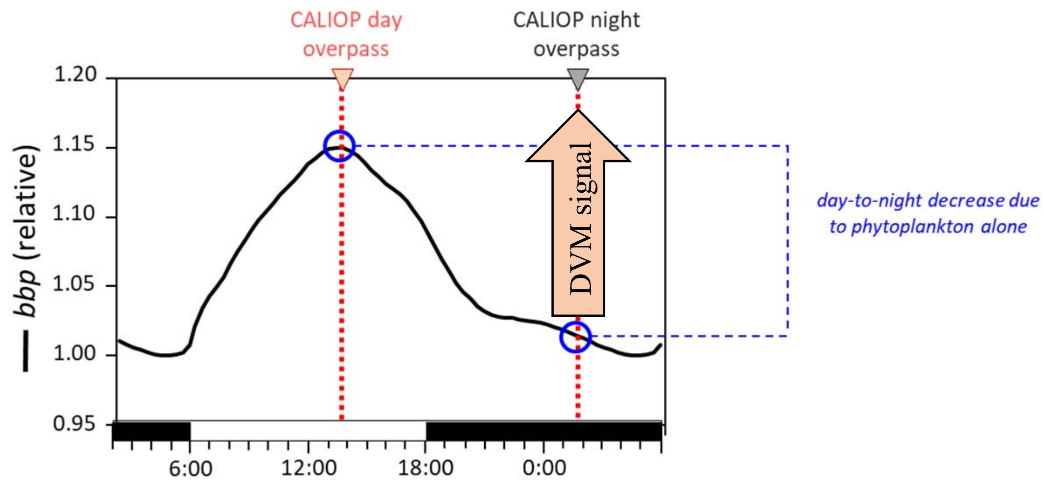
$$\Delta bbp = (bbp^{night} - bbp^{day})/bbp^{day}$$

Two components: Phytoplankton & DVM

Behrenfeld et al. 2016 Nature 576, 257–261

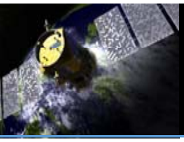
Active Lidar Measurements

The phytoplankton component



Main Point: In the absence of DVM animals the night-day difference in backscatter is expected to be negative due to the phytoplankton diel cycle. As the nighttime abundance of DVM animals increases, the night-day difference becomes more positive

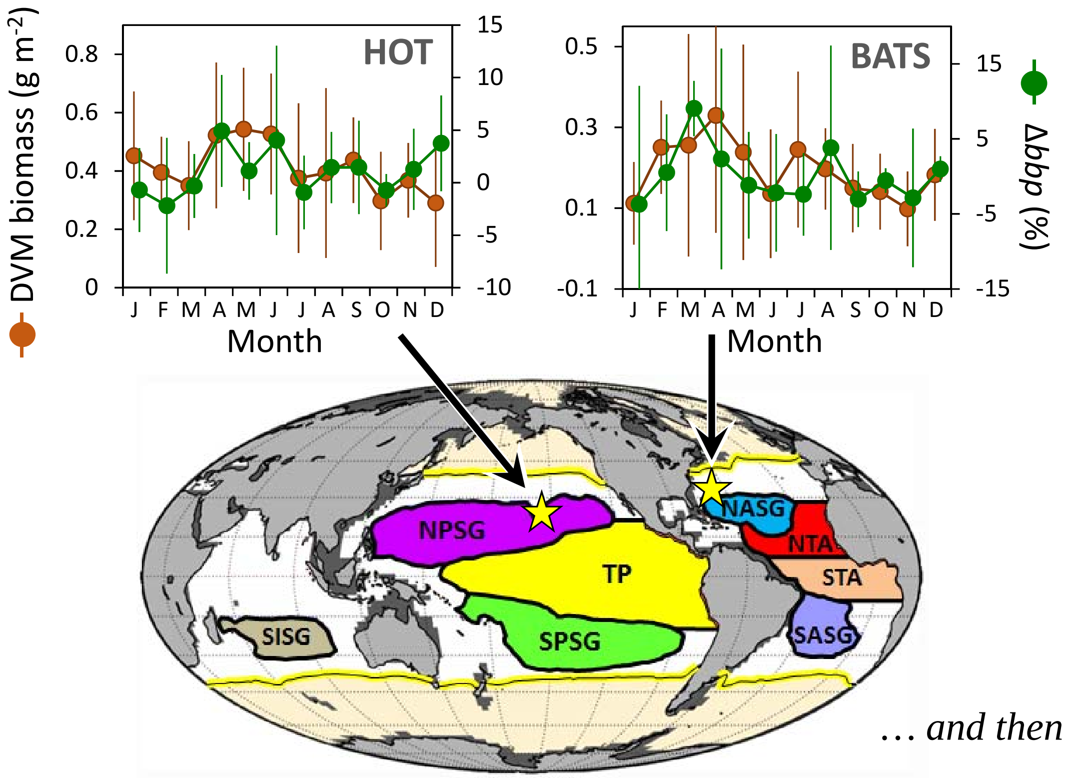
Behrenfeld et al. 2016 Nature 576, 257–261



Active Lidar Measurements

Field data and trends

… after removing the phytoplankton signal, the DVM signal was compared to long-term field DVM records…



… and then we looked at regional trends

Behrenfeld et al. 2016 Nature 576, 257–261

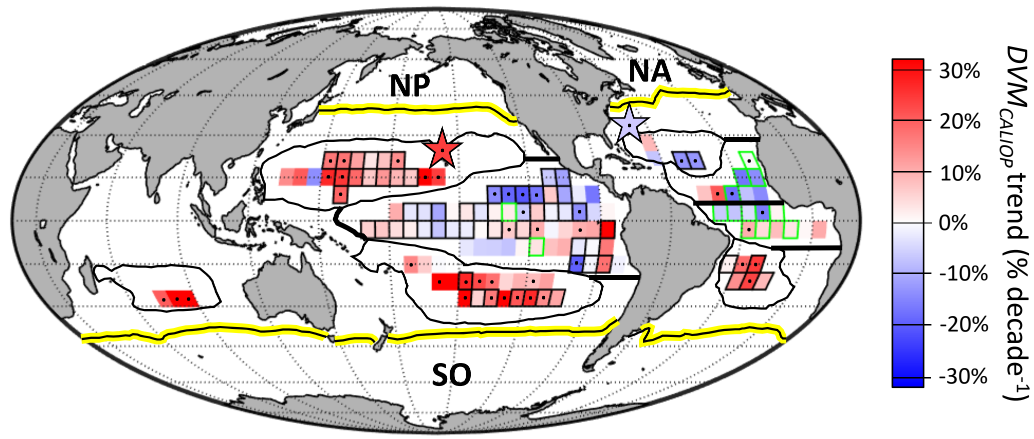
Active Lidar Measurements

● = DVM_{CALIOP} temporal trend significant ($p < 0.05$) for given 6° x 6° bin

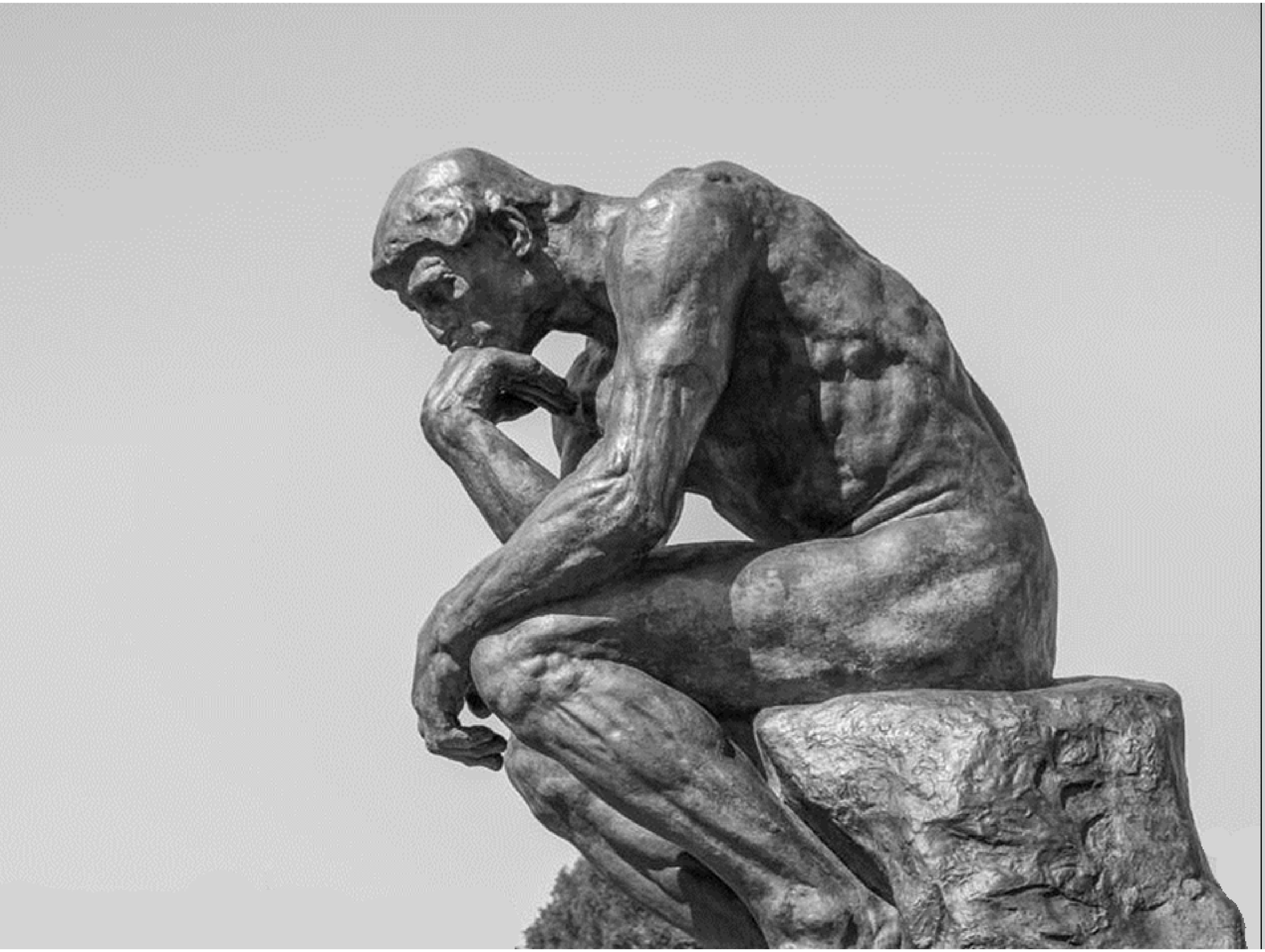
□ = DVM_{CALIOP} significantly ($p < 0.05$) and positively correlated with NPP_{CbPM}

□ (green) = DVM_{CALIOP} significantly ($p < 0.05$) and negatively correlated with NPP_{CbPM}

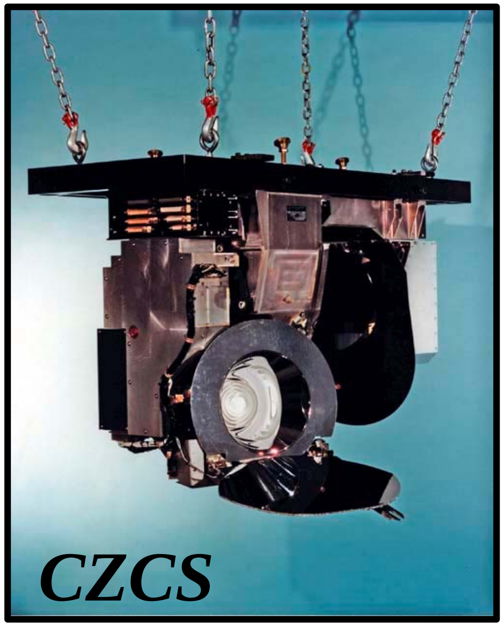
no outline = DVM_{CALIOP} and NPP_{CbPM} not significantly ($p > 0.05$) correlated

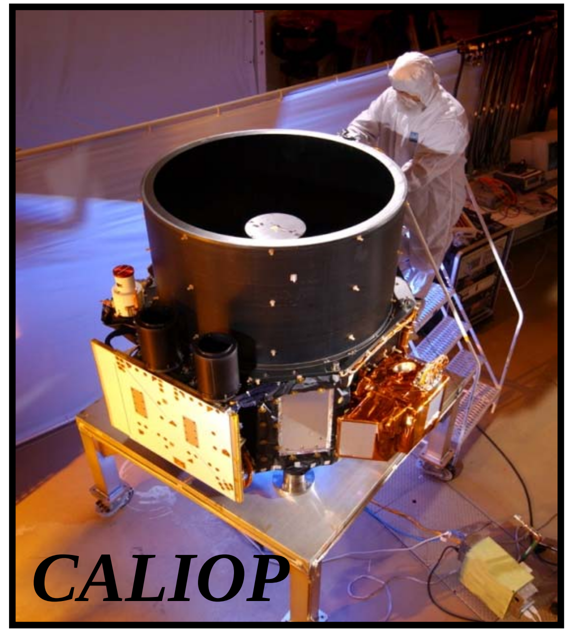


Behrenfeld et al. 2016 Nature 576, 257–261



Thinking forward





CALIOP fortuitously circumvented what is the ‘grave yard’ of many good remote sensing ideas … ‘proof-of-concept’ in space … and has enabled some new science

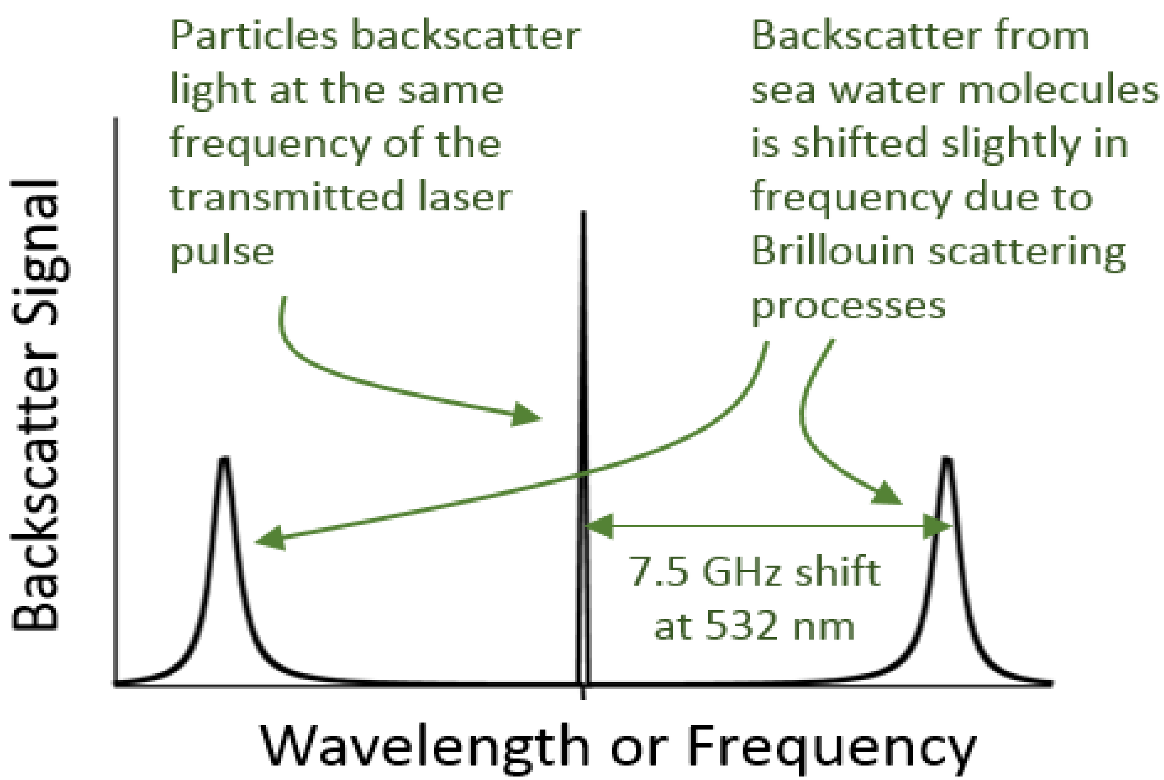
… the question now is, “what could we do if we actually built a satellite lidar optimized for oceanographic research?”

Simple Elastic Backscatter Lidars (e.g., CALIOP)

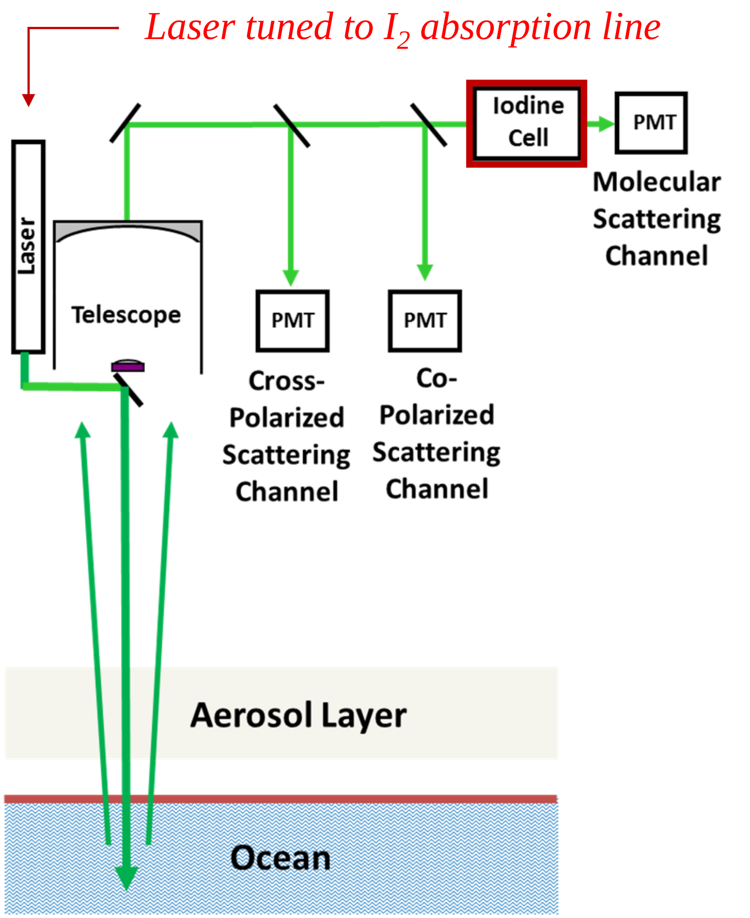
- An 'ill-posed problem': 1 measurement (attenuated backscatter), 2 unknowns (b_{bp}, k_d)
- Requires ancillary data and/or bio-optical assumptions = potential errors

… how do we solve this problem?

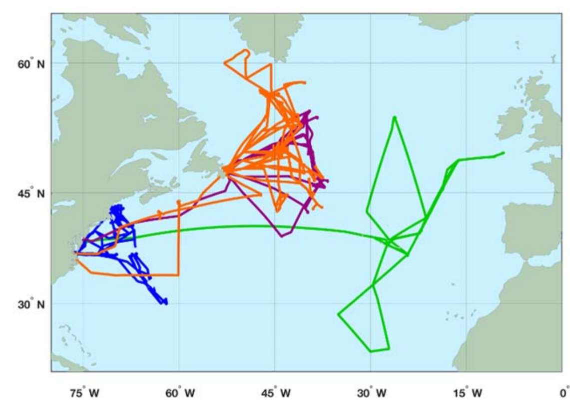
High Spectral Resolution Lidar (HSRL)

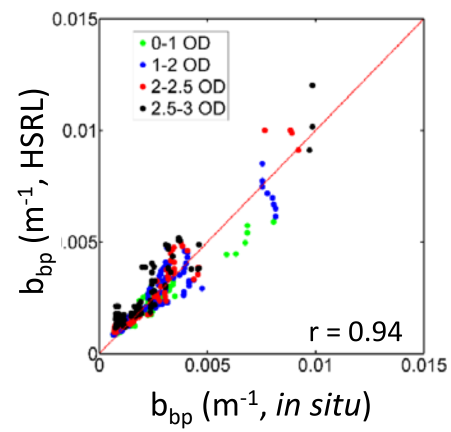


High Spectral Resolution Lidar (HSRL)

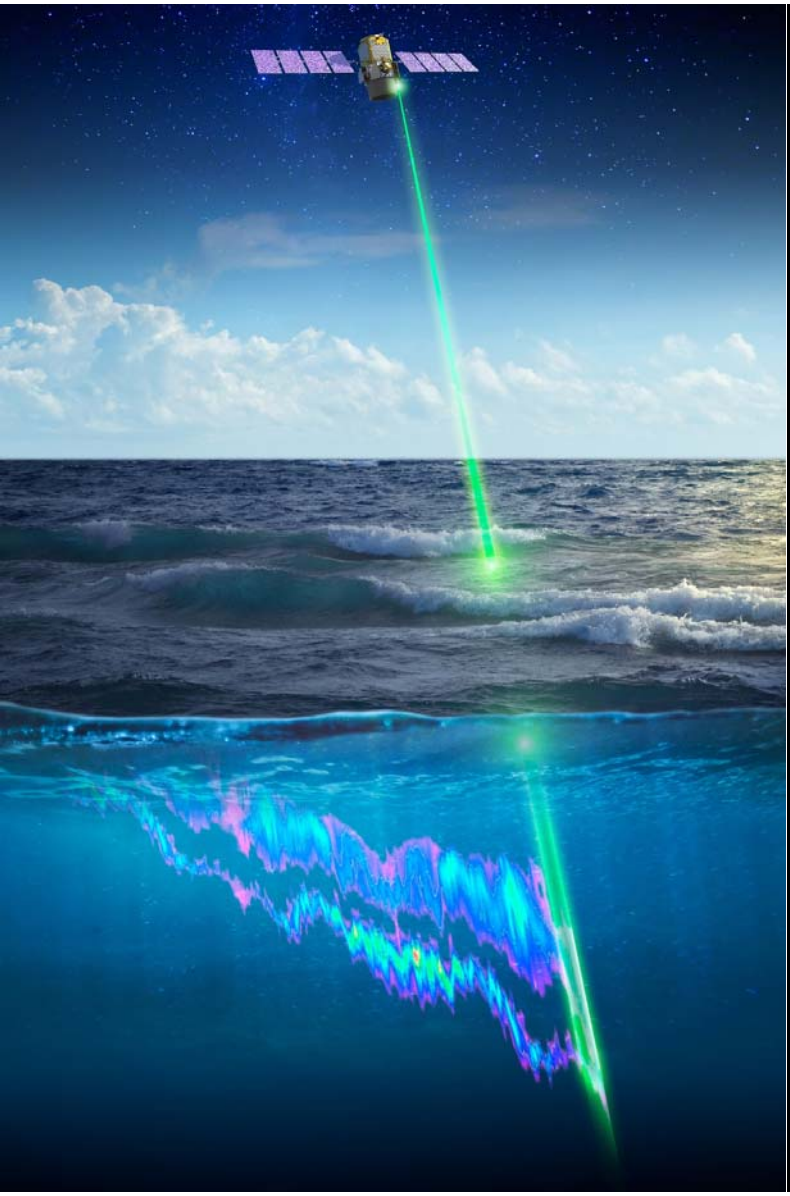


- Standard channels = attenuated water and particulate backscatter
- Filtered channel = attenuated water backscatter
- Water backscatter well known
- A ‘well-posed problem’: 2 measurements, 2 unknowns (b_{bp}, k_d)





Data from *Schulien et al. 2017 Optics Express 25:13577-87*



What would a lidar mission look like if it is actually designed for ocean research?

…above and beyond CALIOP…

- HSRL approach
- Meter-scale vertical resolution
- (option #1) Laser emissions at 1064, 532, & 355 nm
- (option #2) Laser emissions at ~480 nm (Fraunhofer line) – penetration to bottom of photic zone
- chlorophyll fluorescence detection bands

…on the horizon …

- ACCP
- Chinese blue lidar mission
- Small-sat ocean-blue concept

Thank you!

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