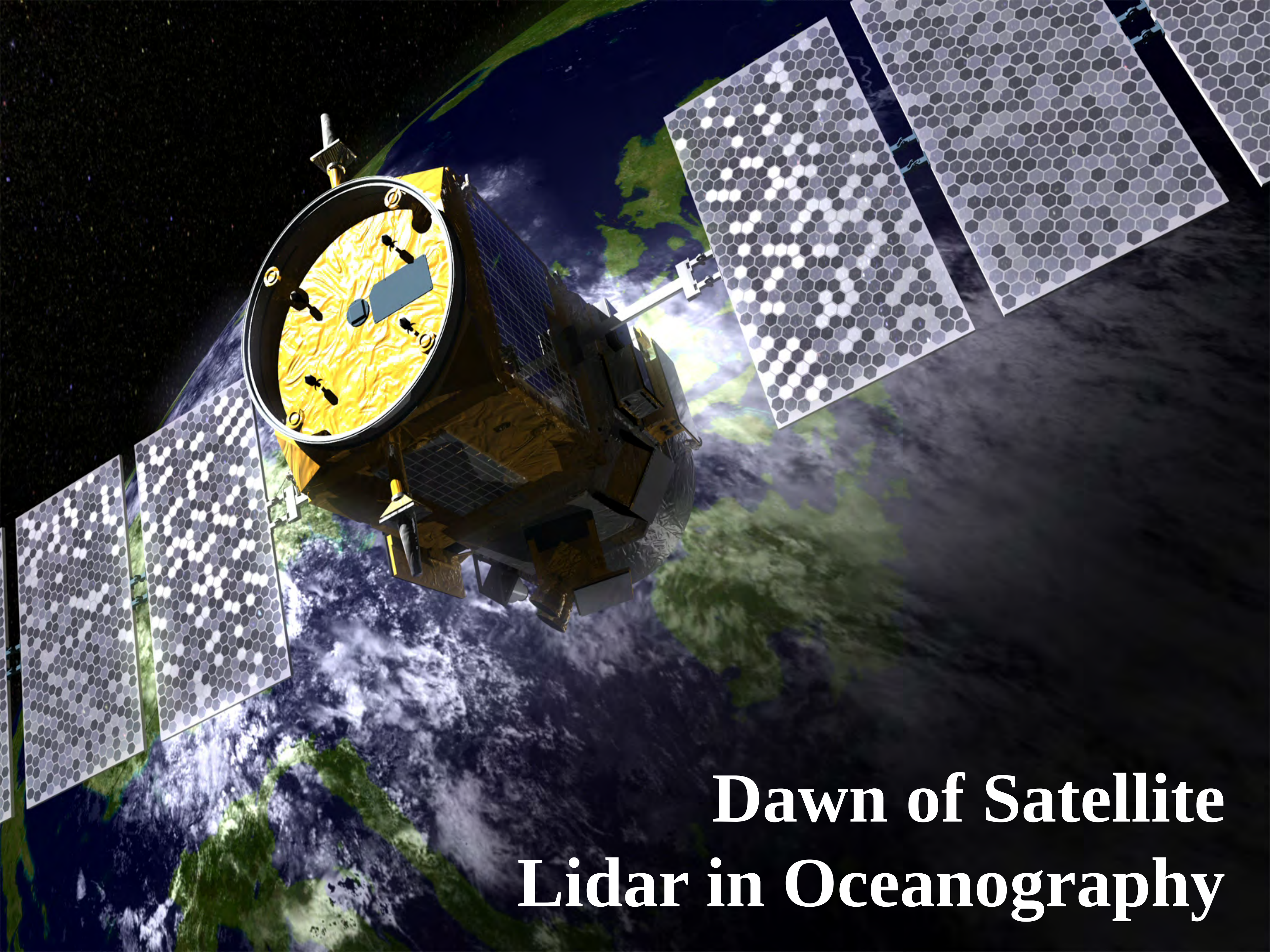
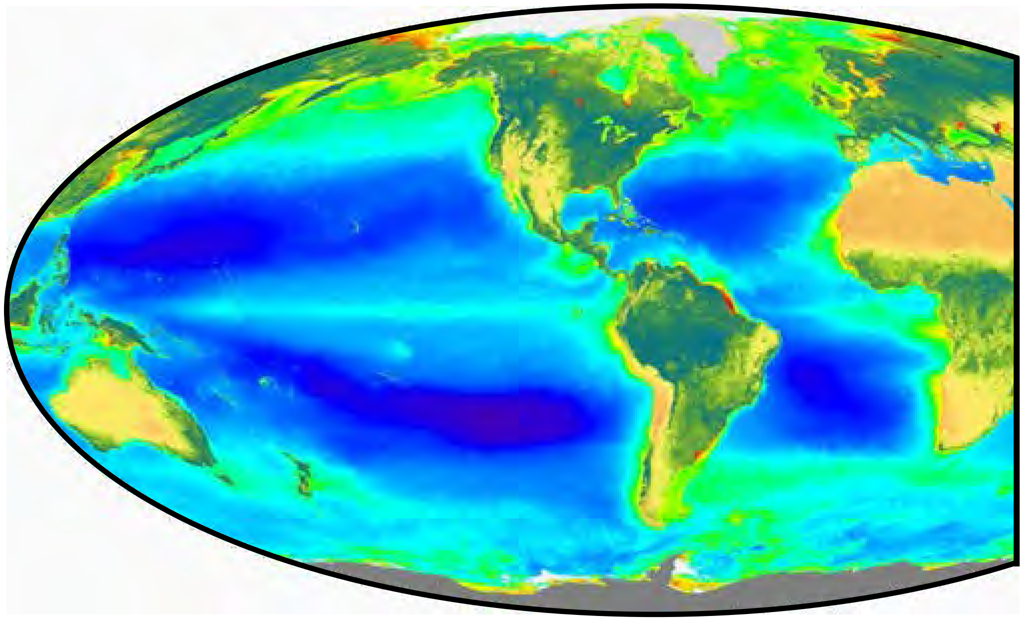


Dawn of Satellite Lidar in Oceanography

Passive Ocean Color Measurements



- atmosphere dominates measured signal and correction is challenging
- ocean component of signal dominated by upper ½ optical depth
- no direct information on vertical distribution of ocean constituents
- an optically integrated property without a direct signal for separating absorption and scattering fractions
- global sampling is compromised by aerosols, clouds, solar angle (in the extreme, polar night)
- no information on plankton properties at night

Active Lidar Ocean Measurements

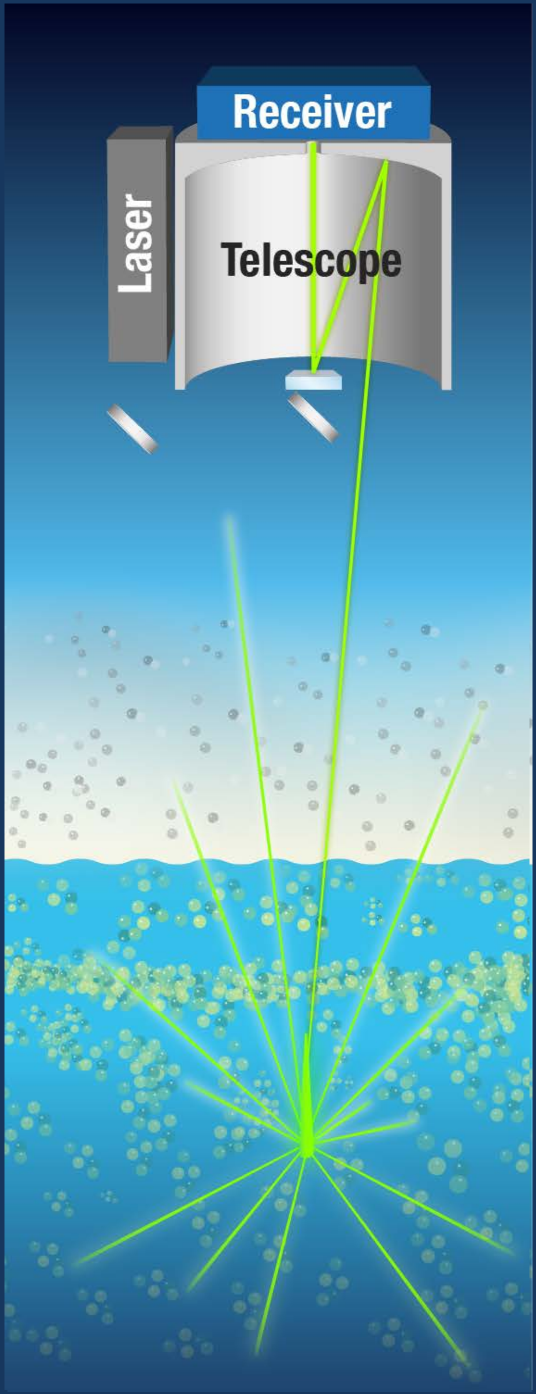
Lidar (Light Detection And Ranging)

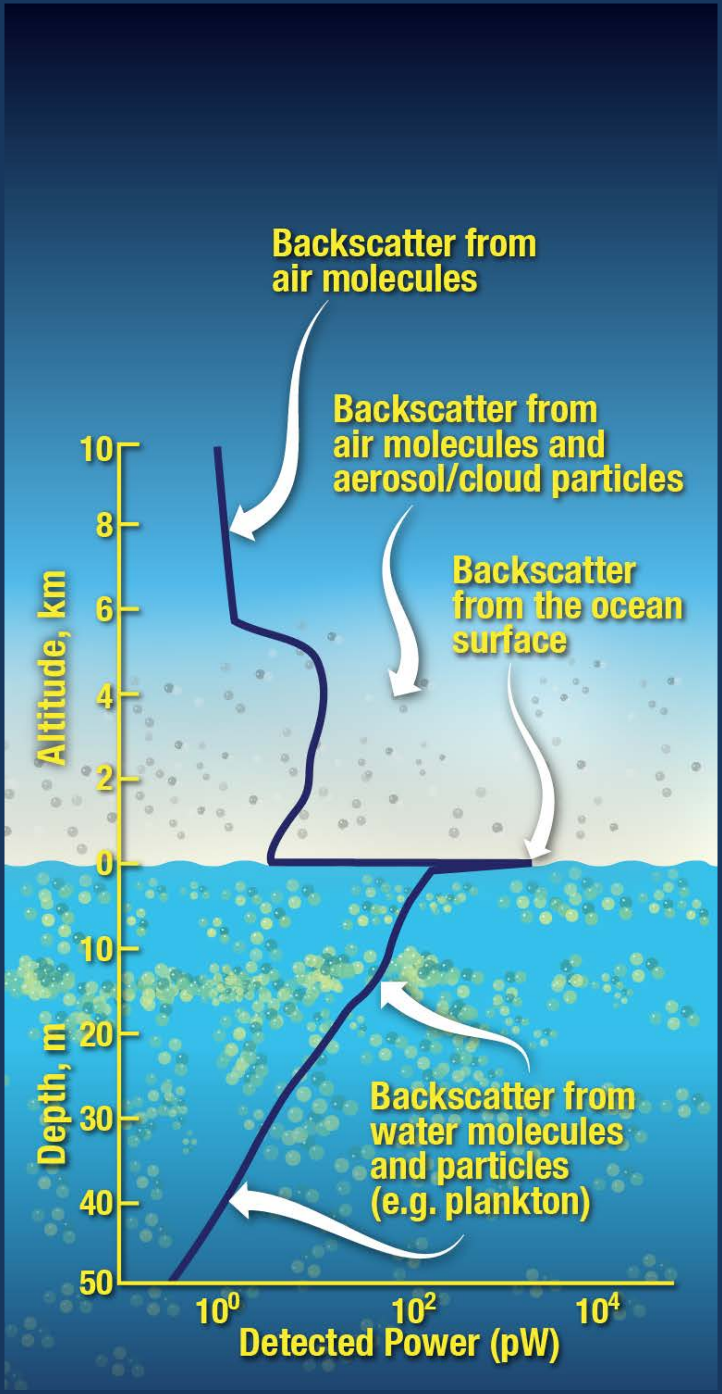
- signal from a known source (laser)
- constant viewing geometry
- minimal atmosphere correction issues
- penetrates deep into photic layer
- resolves vertical structure
- can directly separate absorption and particulate scattering
- retrievals through aerosols/thin clouds & between clouds
- day and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

Roadmap

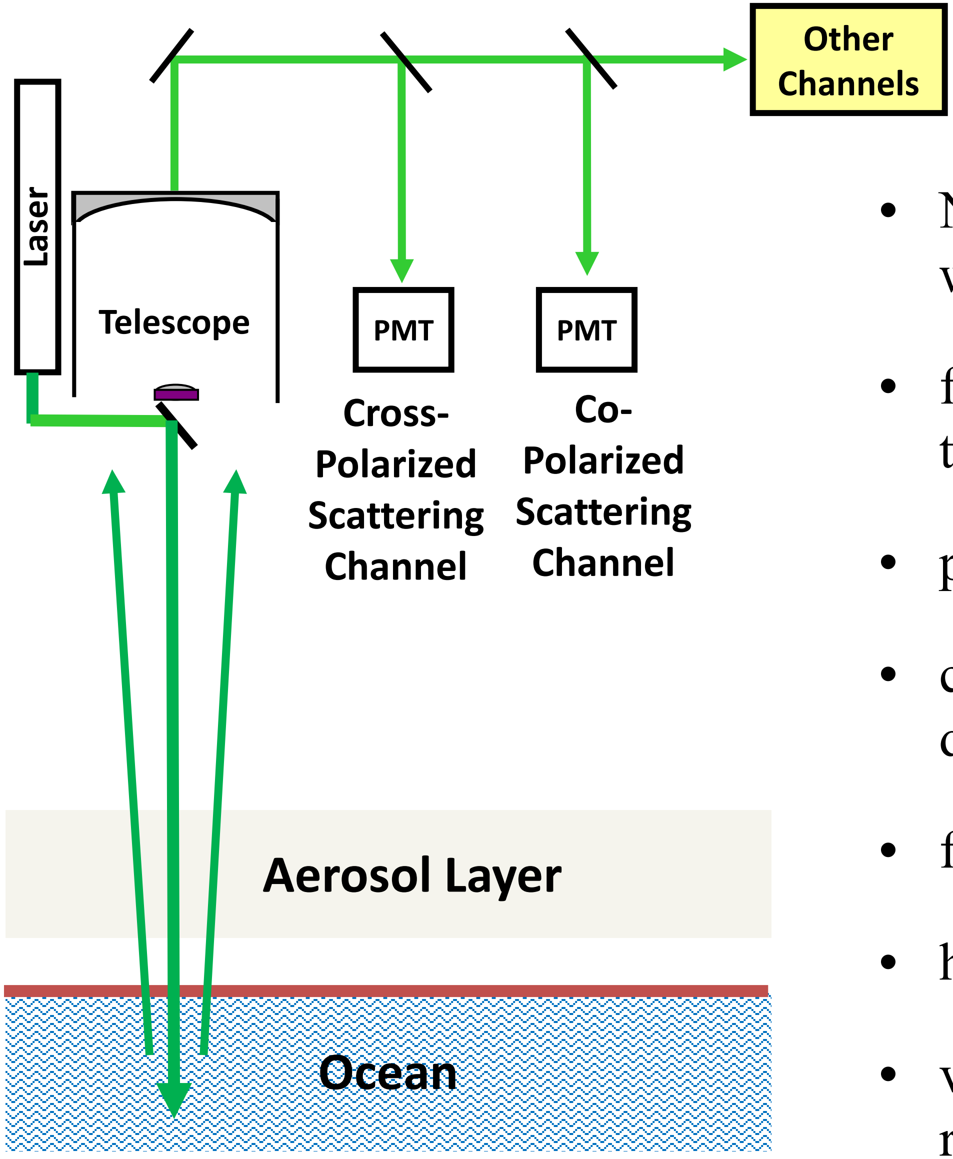
1. How does it work?
2. Notes from the field
3. Going to space
4. Little bit o’ science
5. Solving a problem
6. Looking ahead

Lidar 101: How does it work?



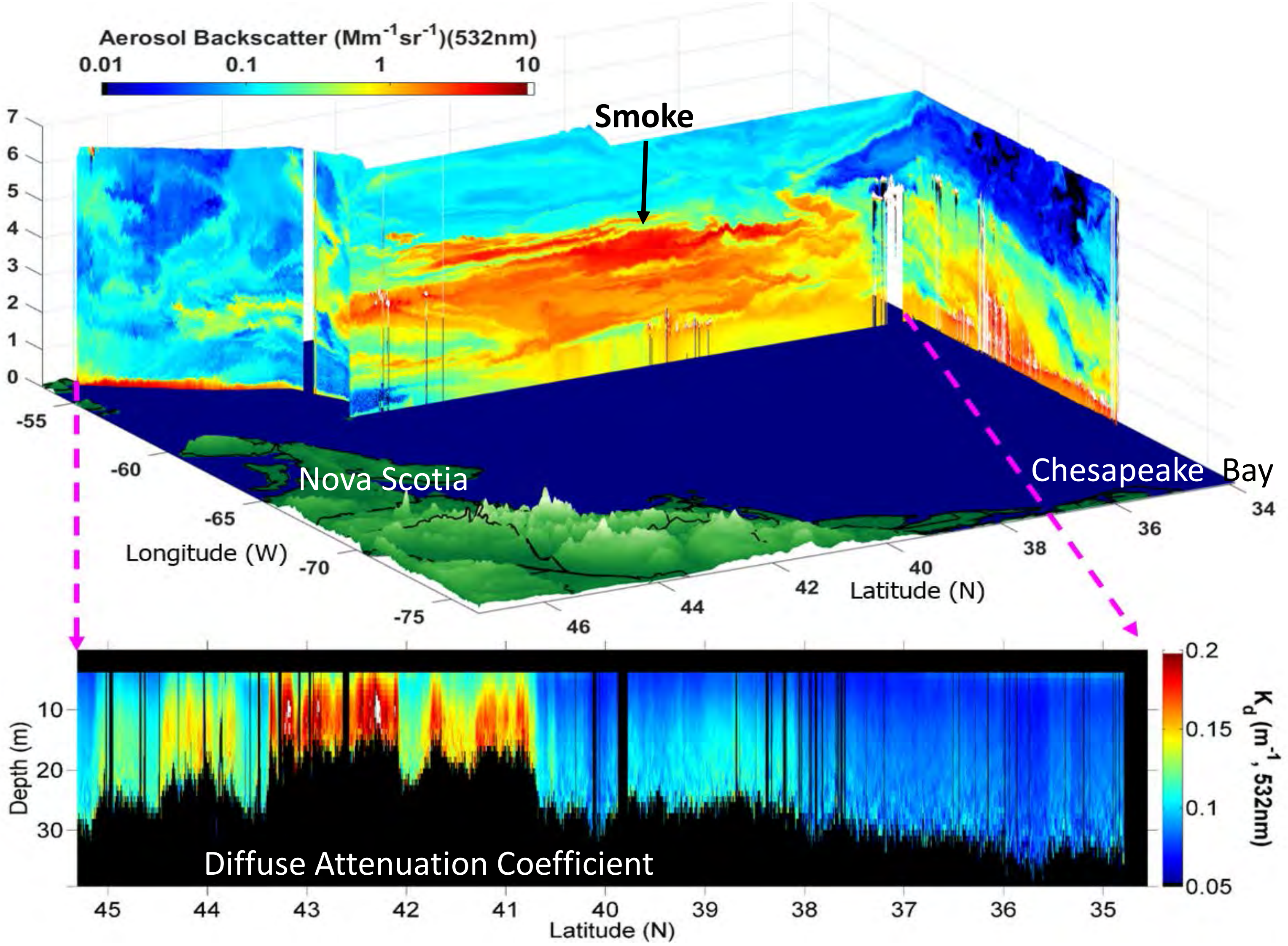


Increasing Information Content



- Nd:Yg laser 1064 nm fundamental wavelength
- frequency double to 532 nm & triple to 355 nm
- polarized emission
- co-polarized & cross-polarized detection
- fluorescence detection bands
- high-resolution spectral filtering
- vertical sampling (detector sampling rate, laser temporal pulse width)

The Lidar ‘Curtain’

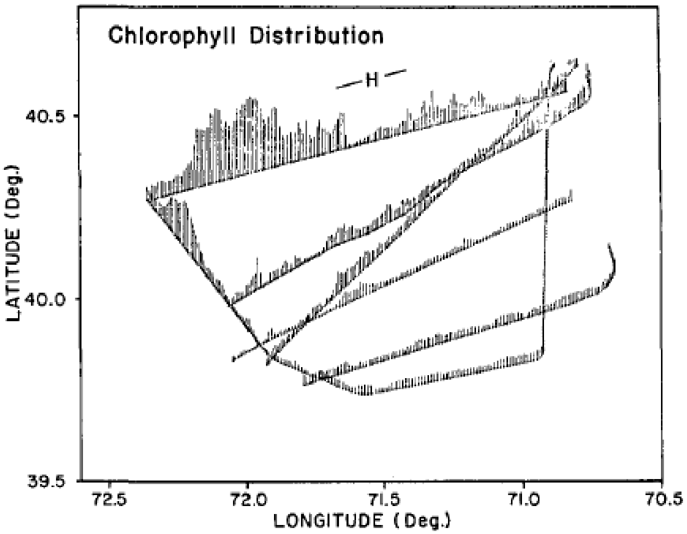


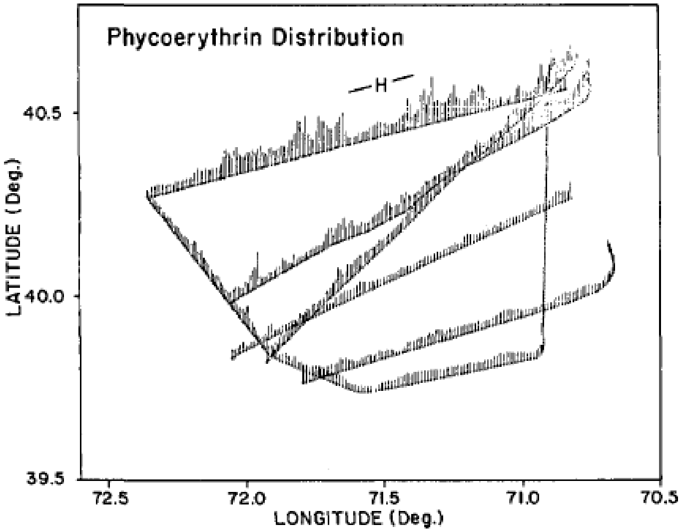
* note, these data are from an advanced airborne lidar system (discussed later)

Notes from the field: Airborne lidar

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

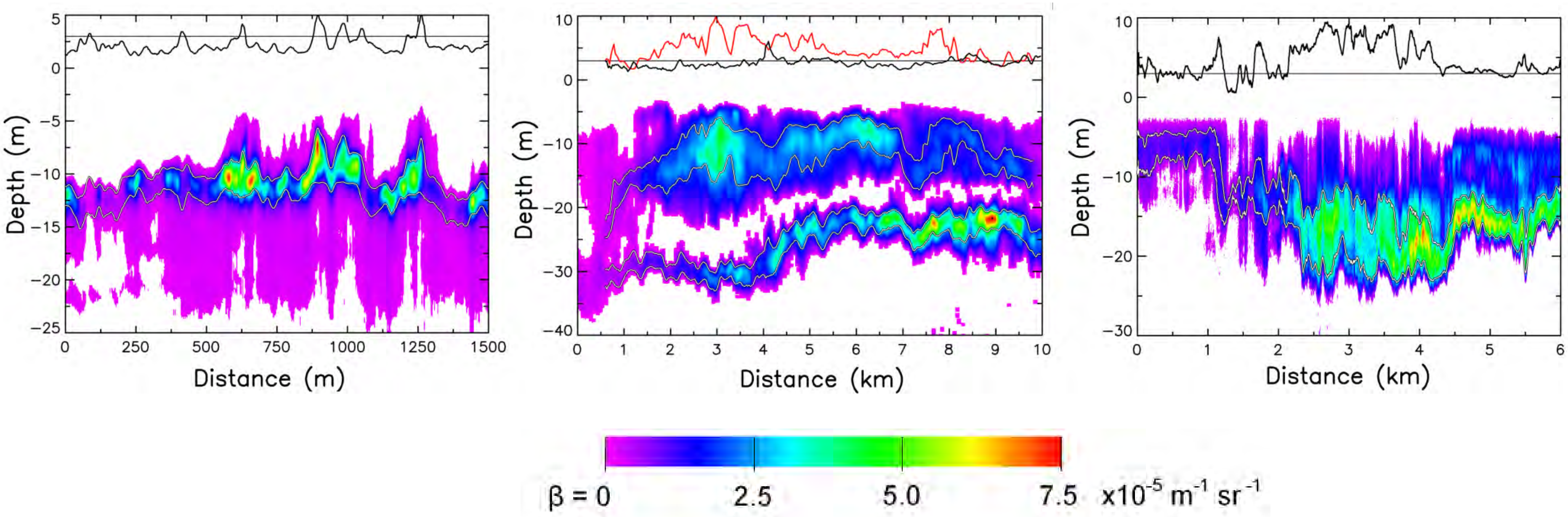




From: Hoge et al. 1986

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 et al. 2014, Churnside & Marchbanks 2015: bio-optical modeling to separate attenuation and backscatter
- Churnside 2015: attenuation, backscatter, & chlorophyll
- Churnside 2016: vertical distribution of net primary productivity

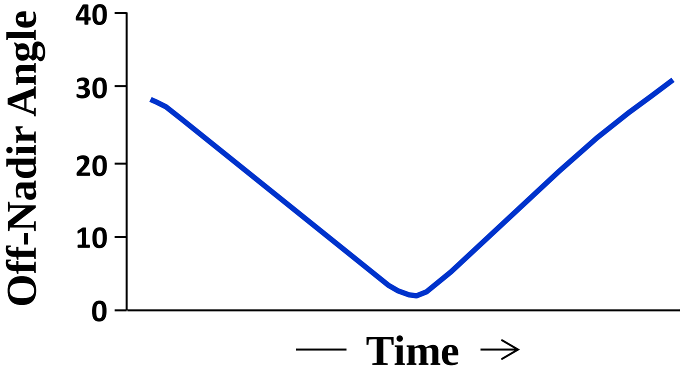


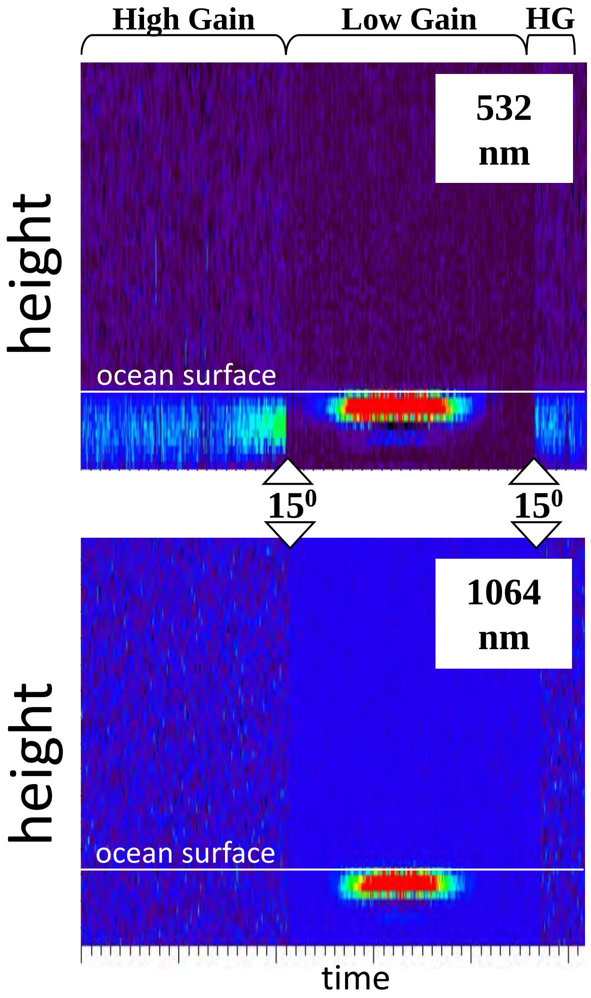
…can we do it from space?

Going to Space

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

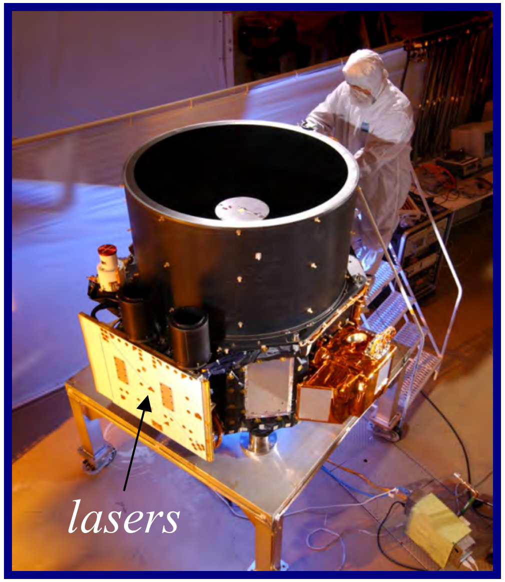


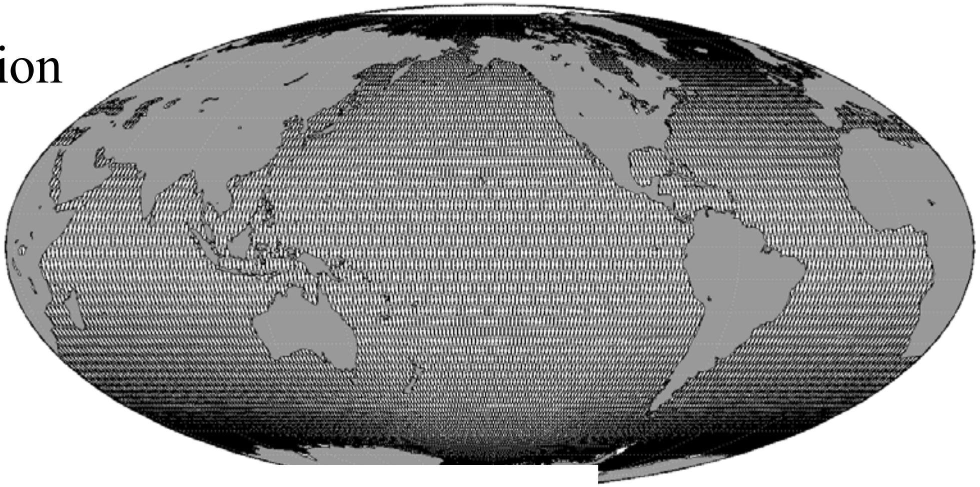


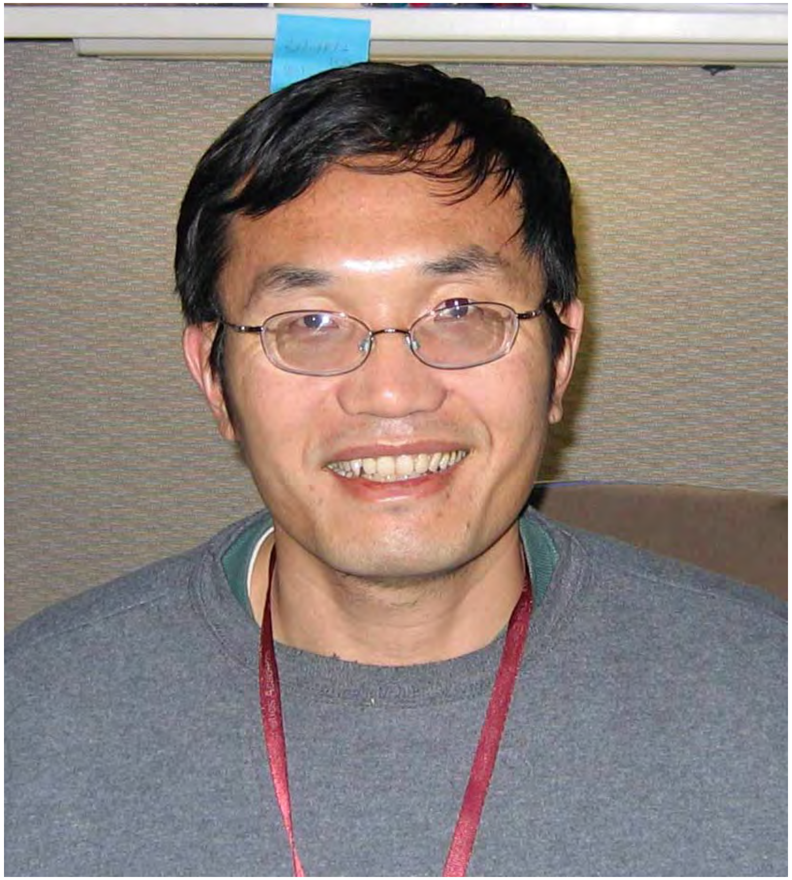
two important things then happened…

#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∥, 532 ⊥ , 1064 nm)
- 1 meter telescope
- 100 m footprint
- 30 m air / 23 m water vertical resolution
- polar orbiting, 16 day repeat cycle ↵
- measurements both day and night

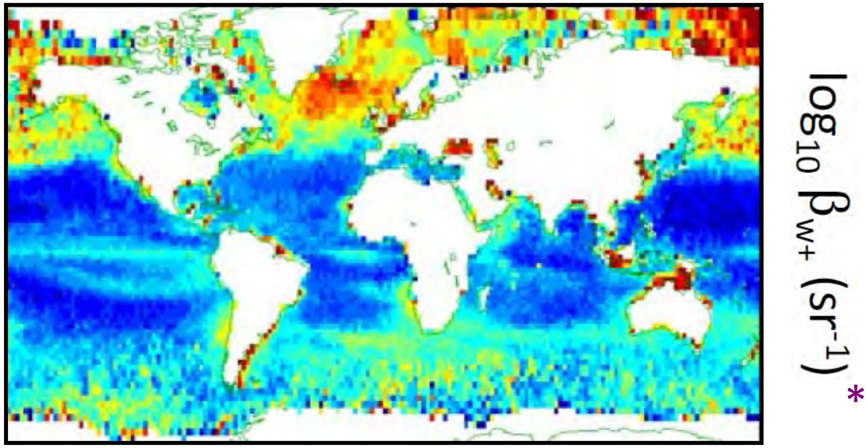






#2. Yongxiang 'Yong' Hu

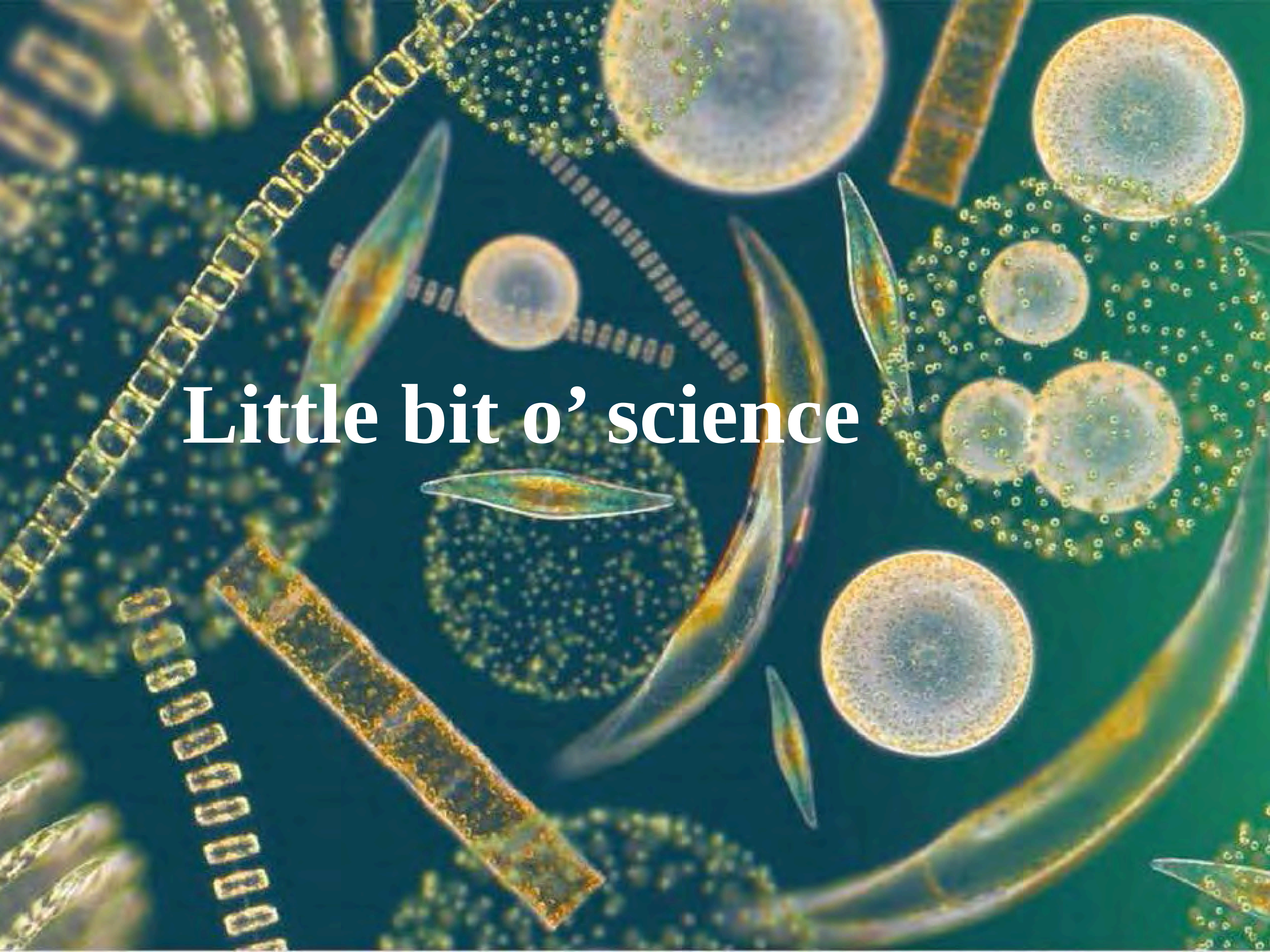
- OCRT 2007



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

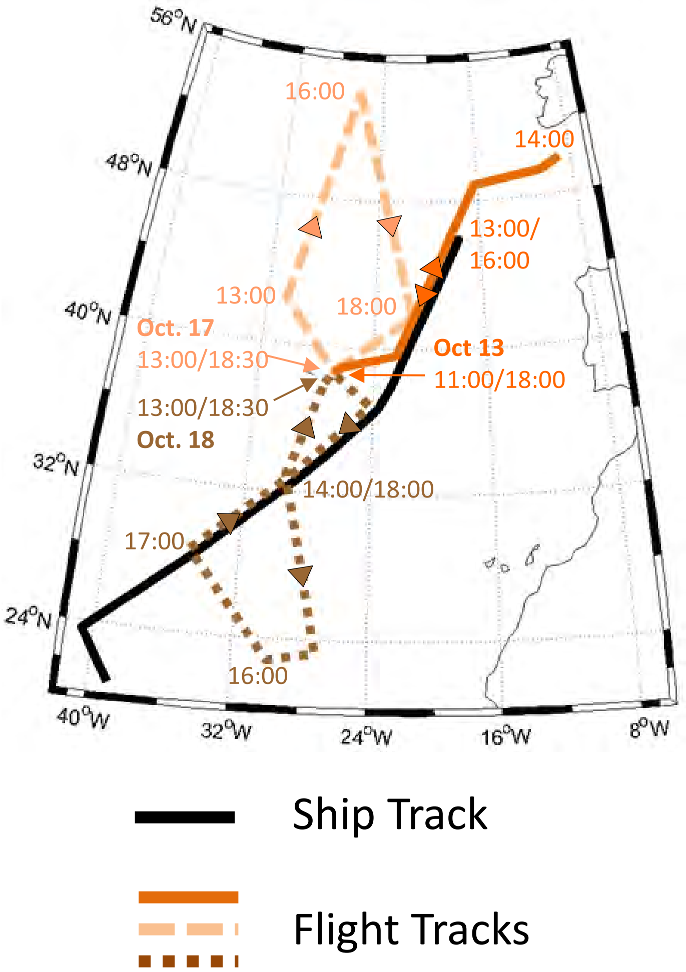
Churnside et al. 2013. *Rem. Sens*. 5:3457-75 (evaluate detection, MODIS comparison)

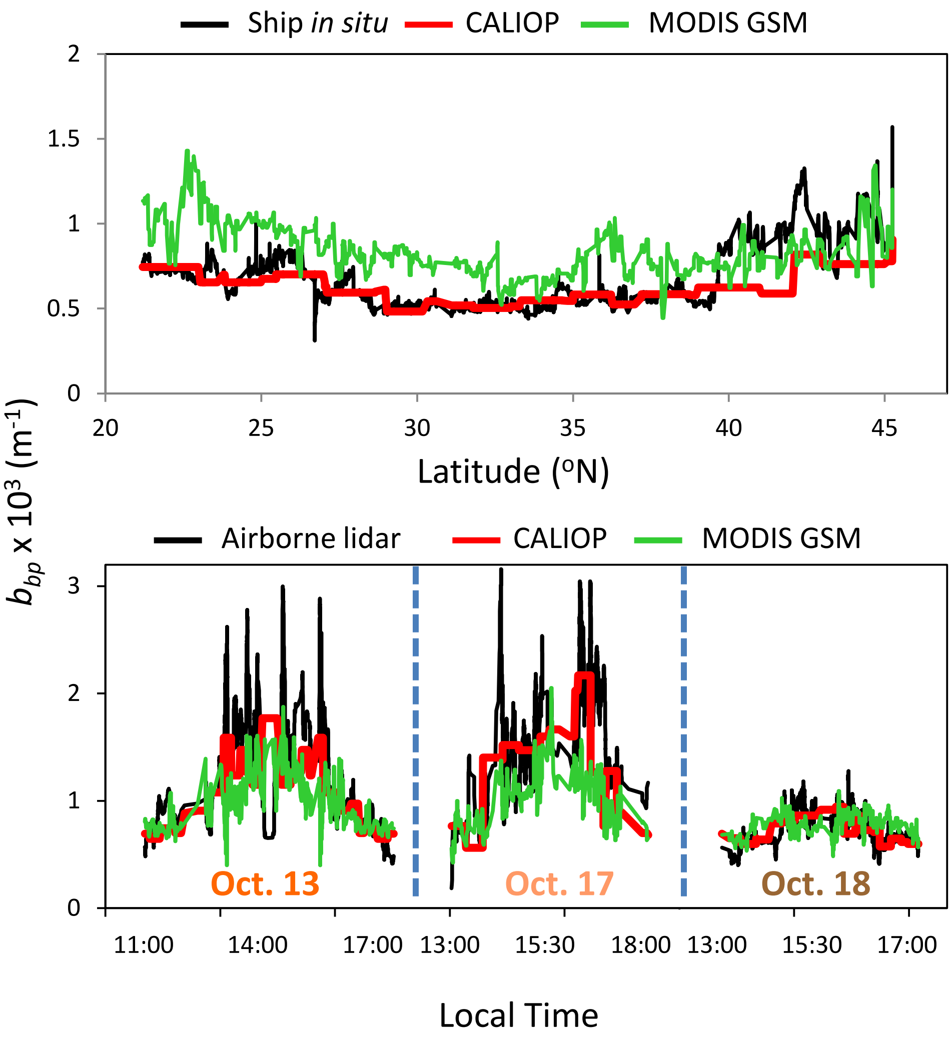
Behrenfeld et al. 2013 *Geophys. Res. Lett*. 40, 4355-60 (field val, geophysical prod's)



Little bit o’ science

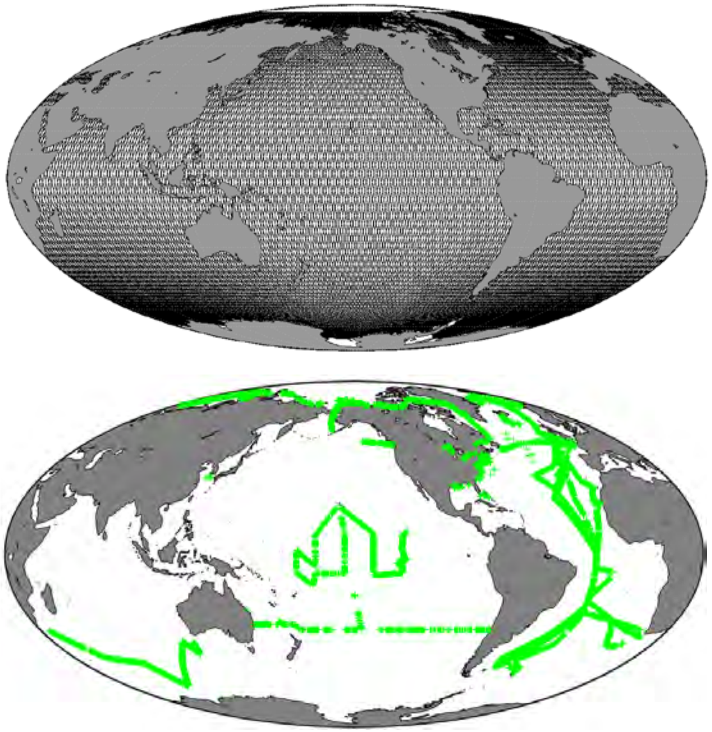
Field-testing Retrievals

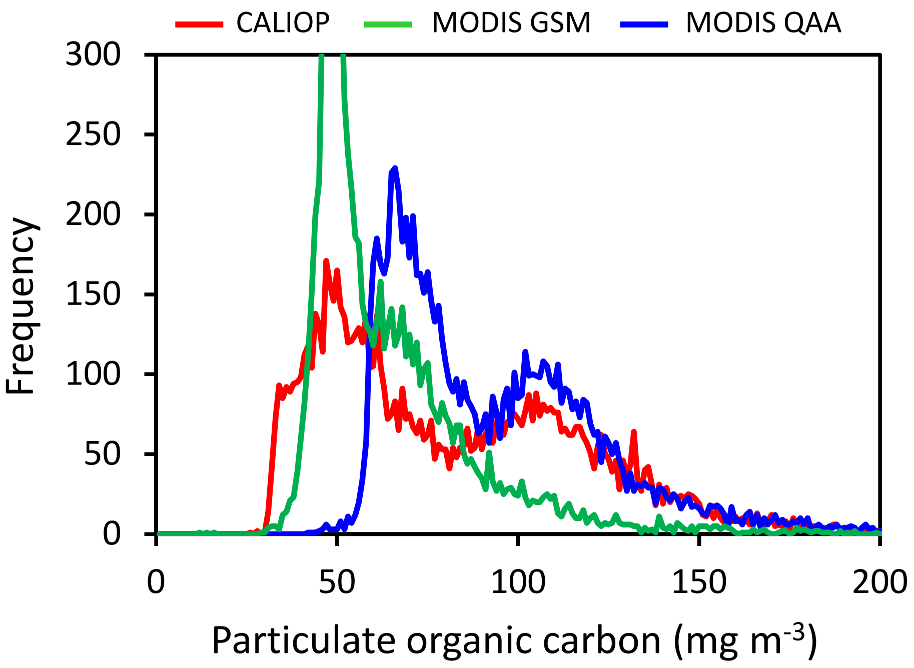




Behrenfeld et al. 2013 Geophys. Res. Lett. 40, 4355-4360

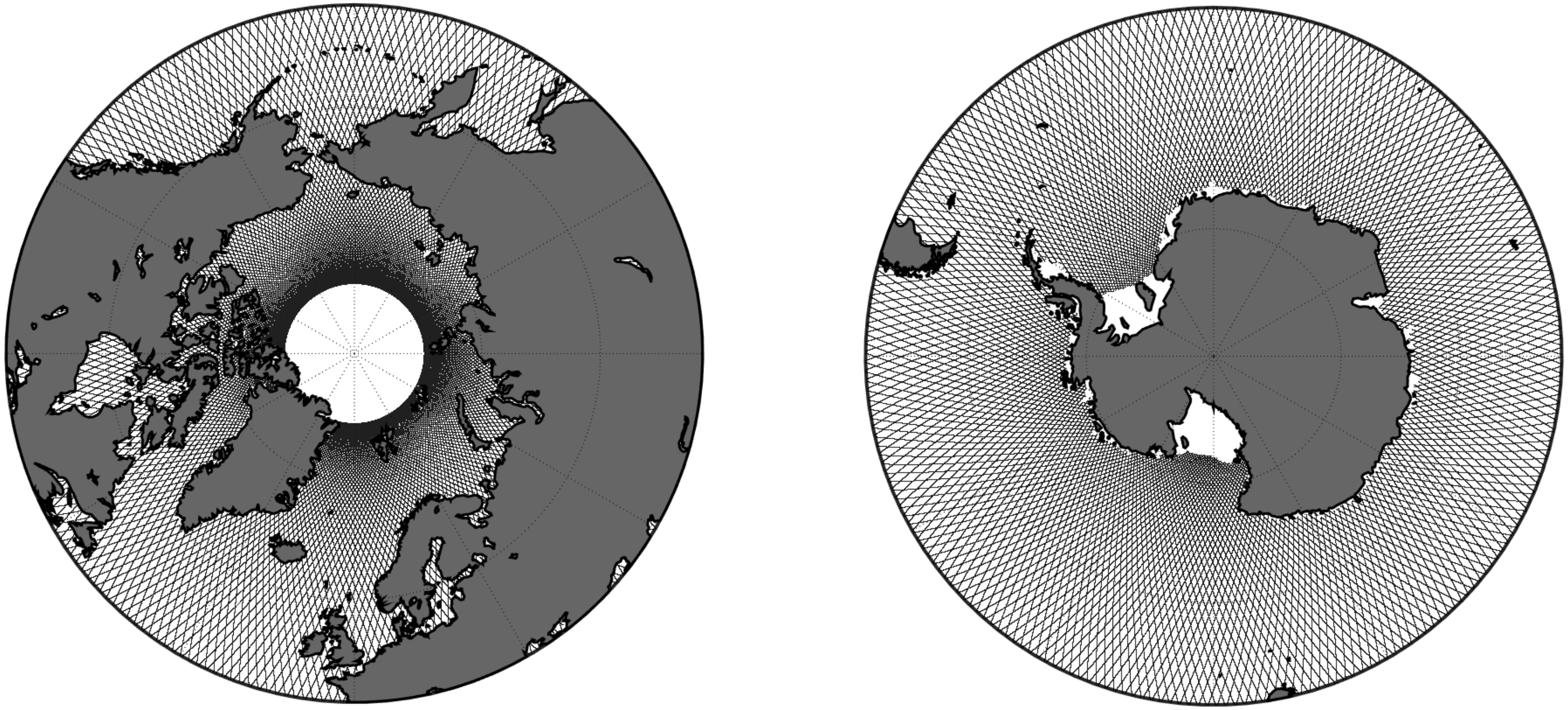
Plankton Stocks with a Satellite Lidar





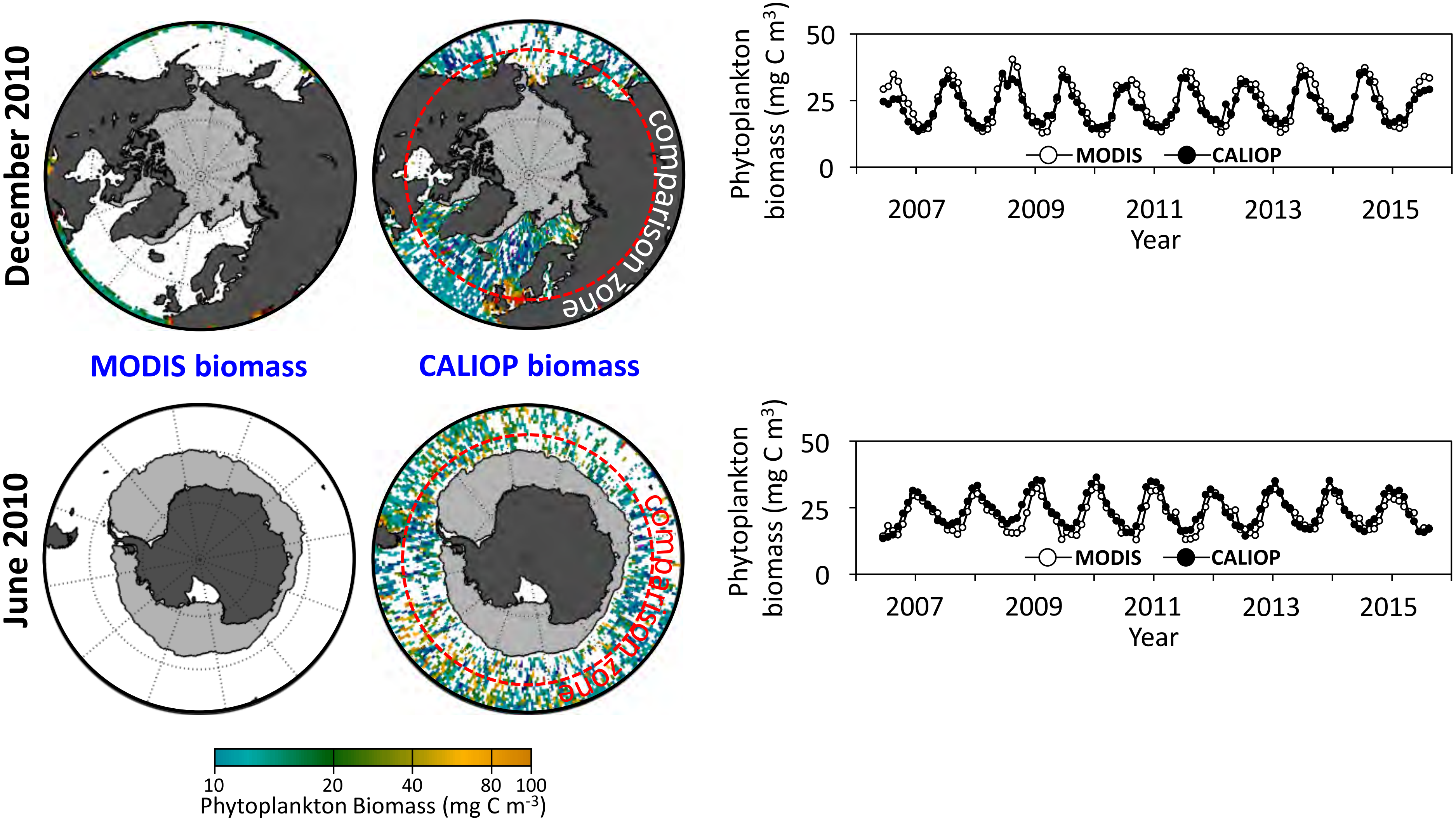
Behrenfeld et al. 2013 Geophys. Res. Lett. 40, 4355-4360

Polar Systems: Where Lidar Really Shines



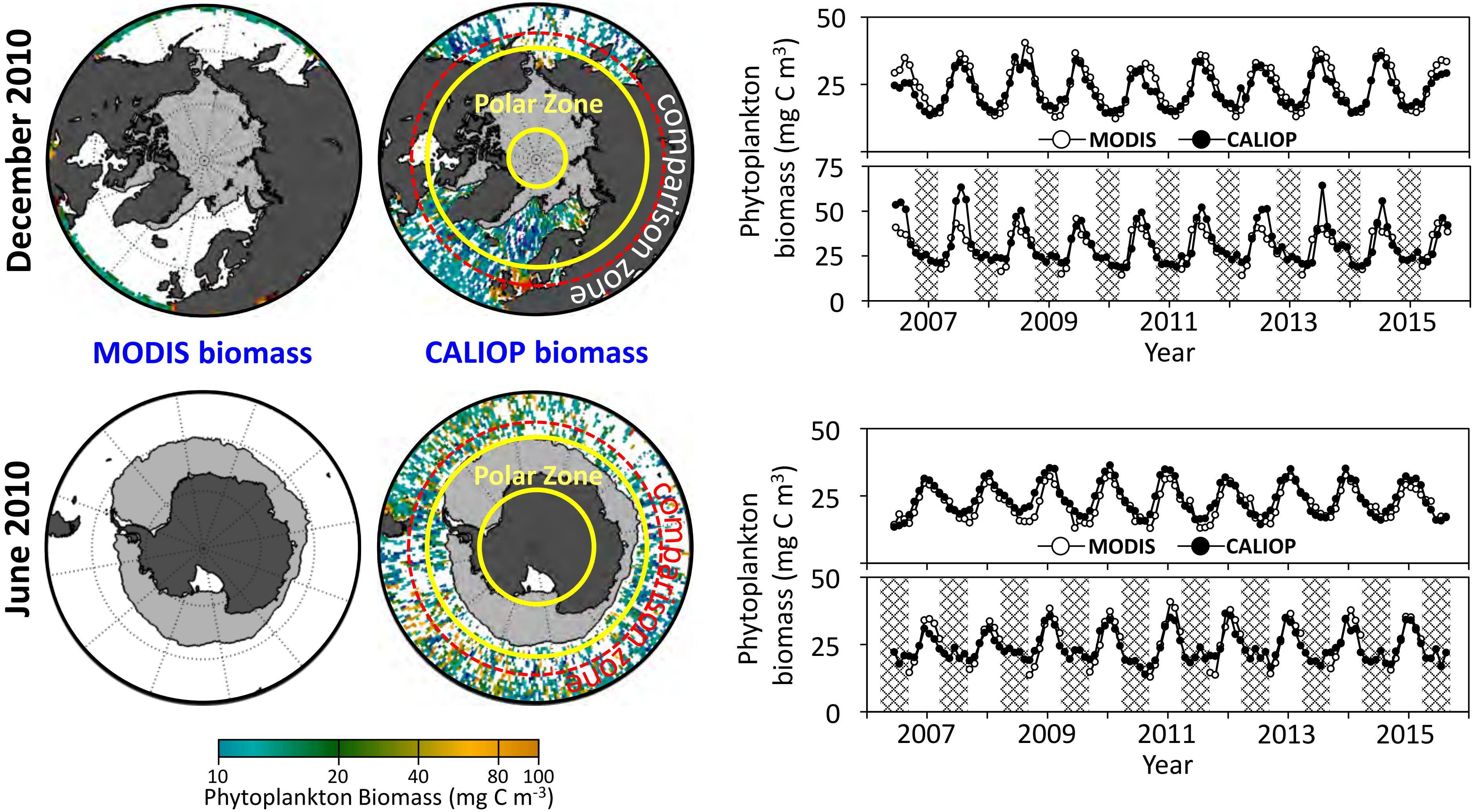
Behrenfeld et al. 2016 Nature Geoscience 19, 118-122

CALIOP Shines on Polar Ecosystems



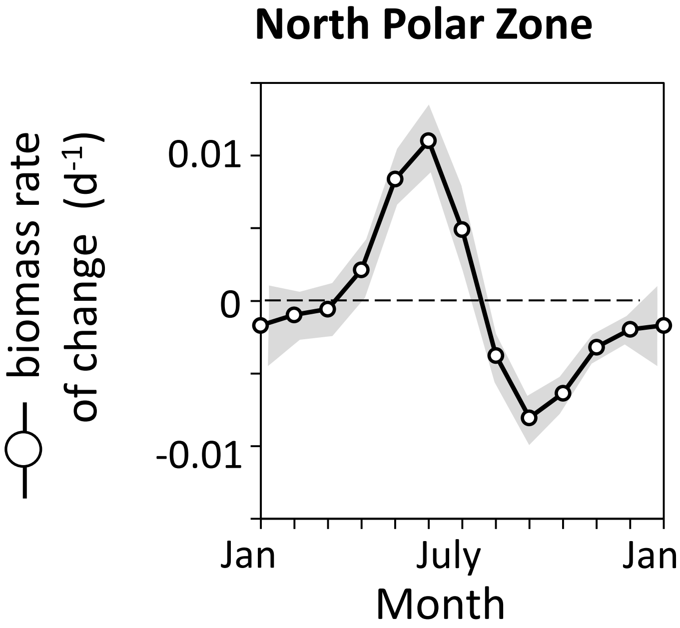
Behrenfeld et al. 2016 Nature Geoscience 19, 118-122

CALIOP Shines on Polar Ecosystems



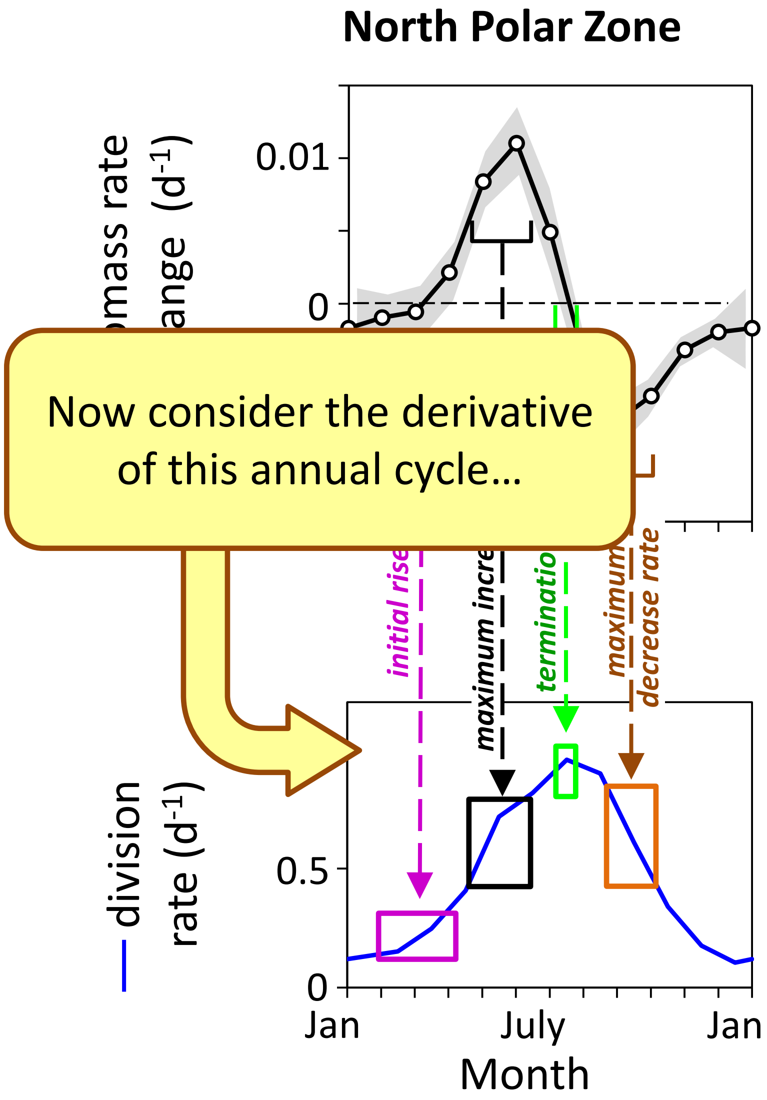
Behrenfeld et al. 2016 Nature Geoscience 19, 118-122

Polar Biomass Dynamics



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

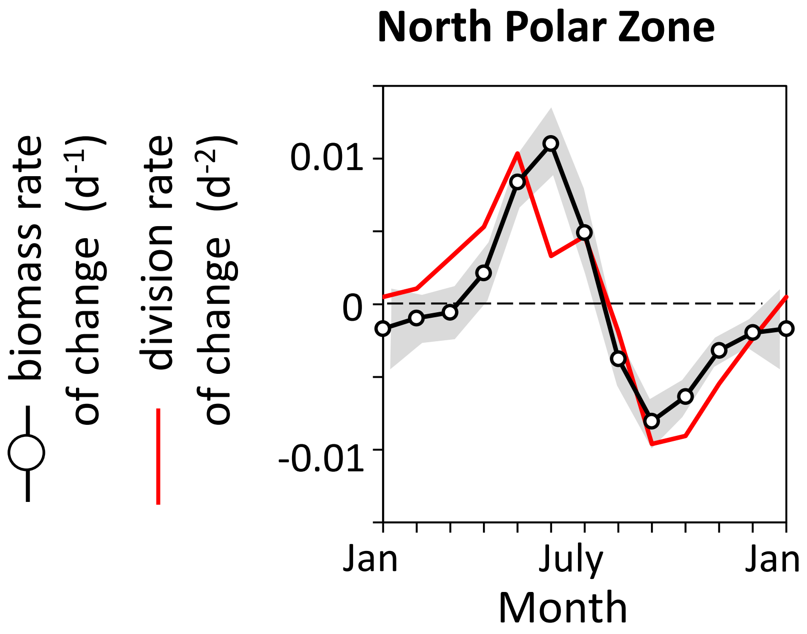
Polar Biomass Dynamics



Now consider the derivative of this annual cycle…

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

Polar Biomass Dynamics



The temporal lag in predator (zooplankton, viruses, etc) responses to phytoplankton division rate changes causes the annual cycle in biomass to track accelerations and decelerations in division rate

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

Summary

- CALIOP fortuitously circumvented what is the death of many good ideas … proof-of-concept in space

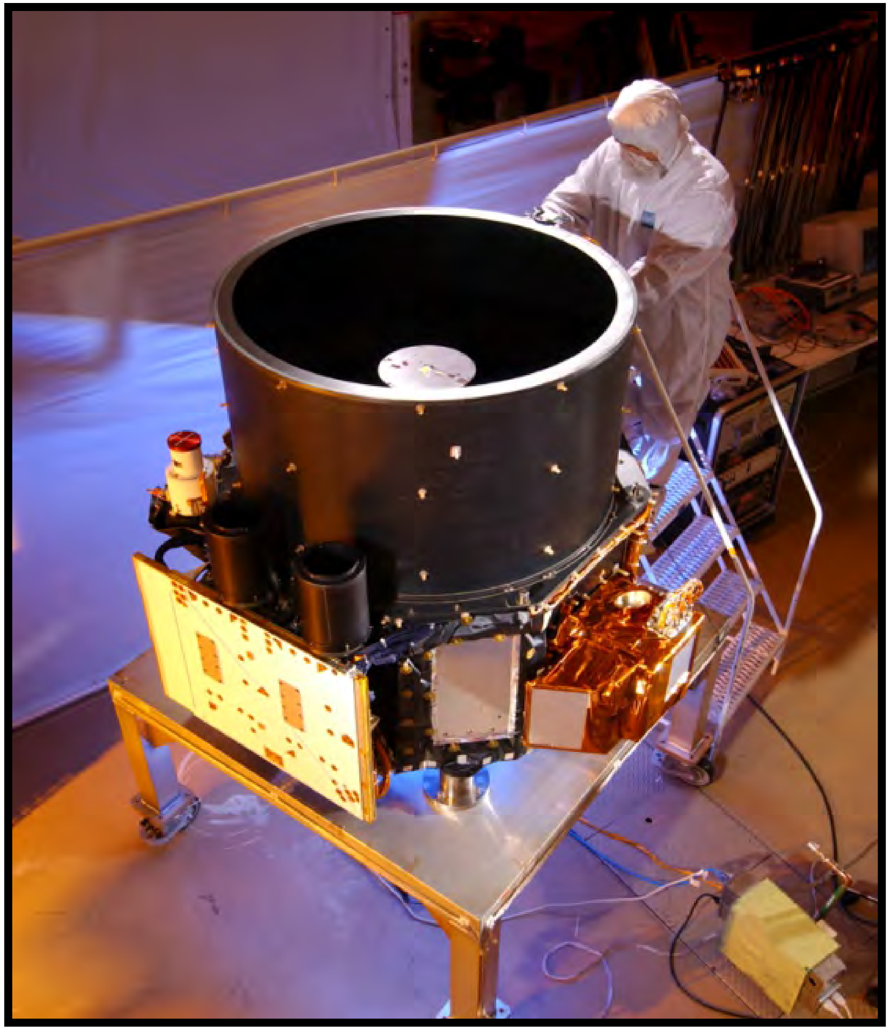
- CALIOP's global observations provide independent assessments of plankton stocks and new constraints for ocean color algorithms

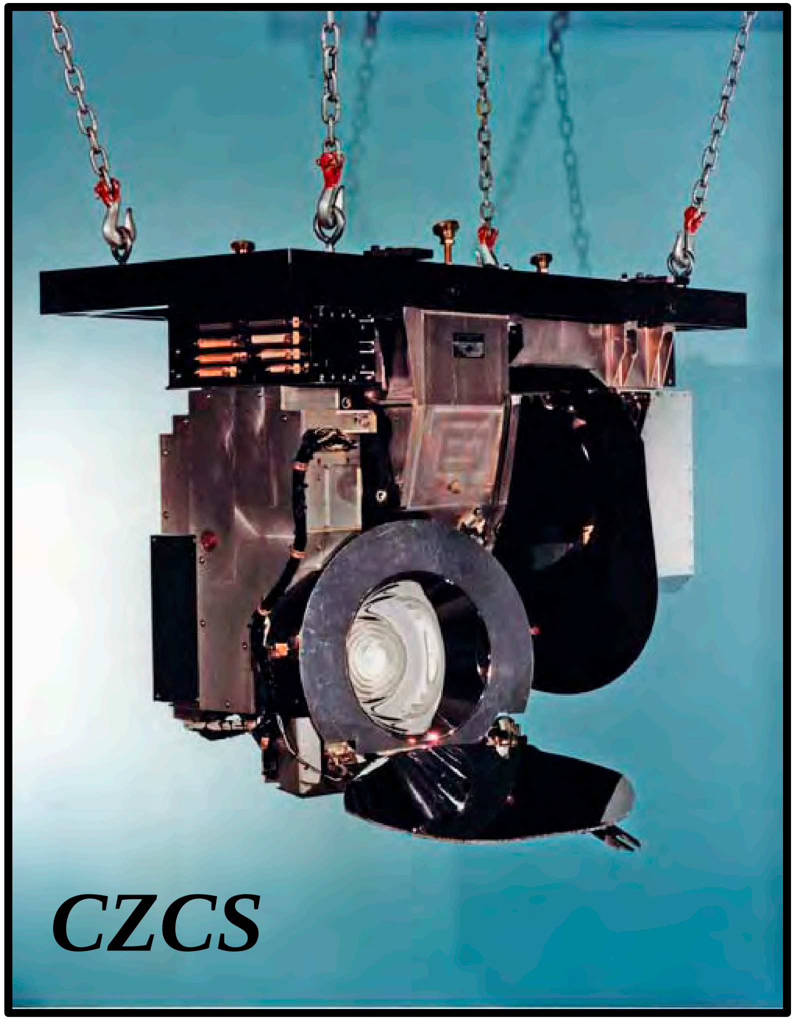
- CALIOP's polar observations address major challenges for ocean color sensors, 'fill in' missing pieces of plankton annual cycles, and provide new ecological insights on plankton 'boom-bust' cycles

The lidar era in satellite oceanography has arrived…

Solving a problem

‘Proof-of-Concept’



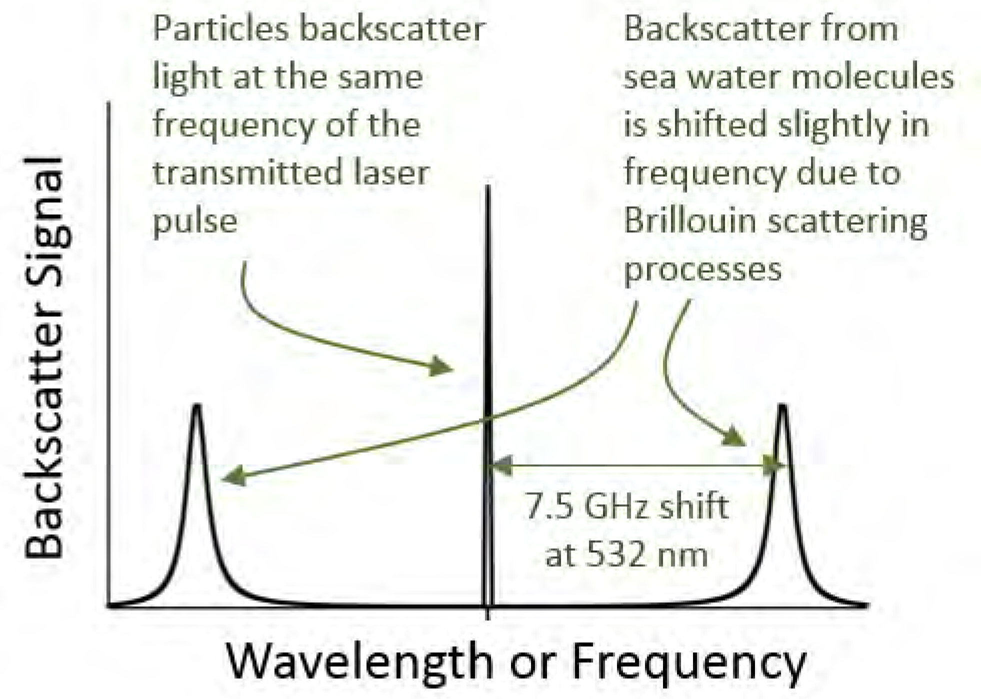


Simple Elastic Backscatter Lidars (e.g., CALIOP)

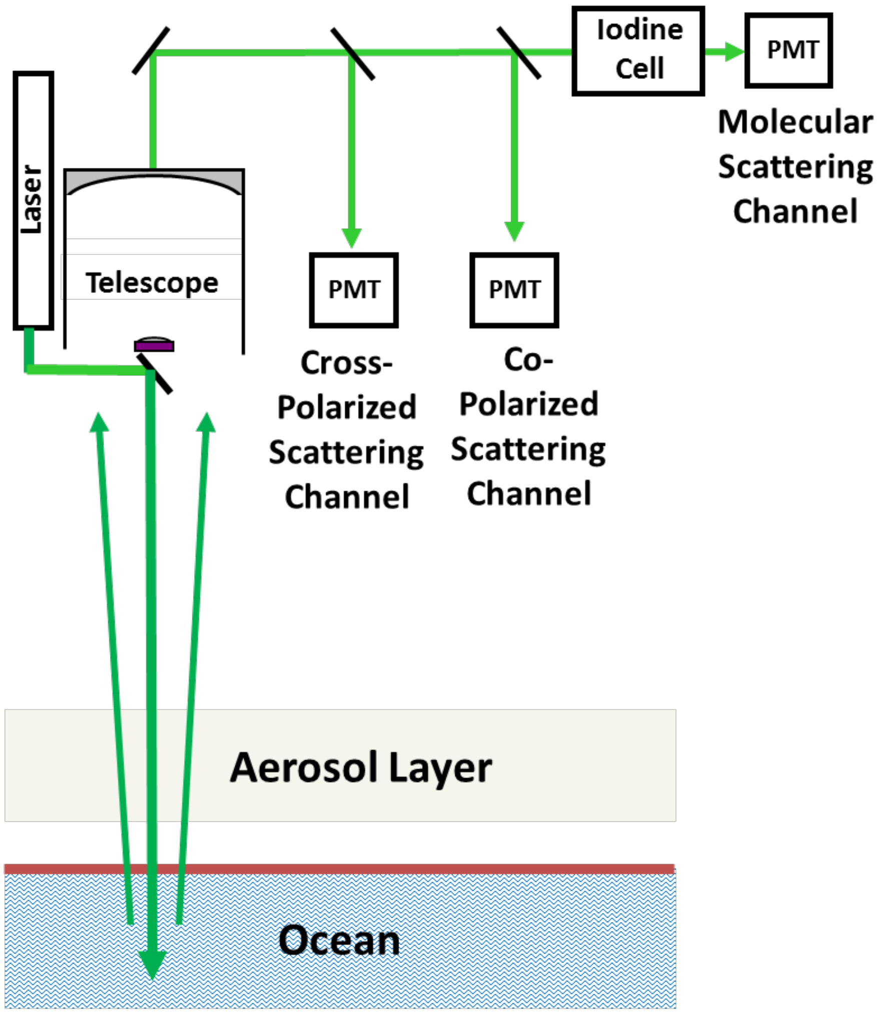
- An 'ill-posed problem': 1 measurement (attenuated backscatter), 2 unknowns (b_{bp}, k_d)
- Ancillary data and/or bio-optical assumptions required to solve, with large potential errors
- Retrieval starts from top of profile and attenuation is removed at each level by assuming an extinction-to-backscatter ratio. Errors accumulate with distance from sensor
- Science value will be far greater for a lidar providing independent, calibrated retrievals of b_{bp} and k_d without propagation of errors …

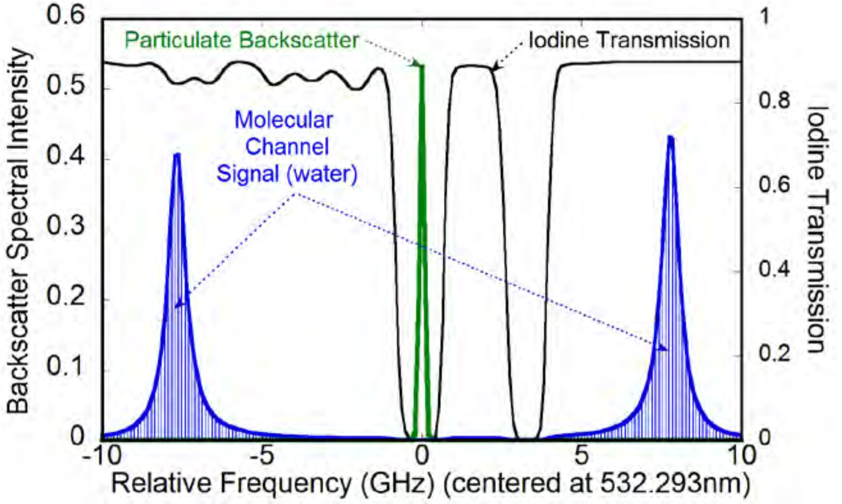
… **can this be done?**

High Spectral Resolution Lidar (HSRL)



High Spectral Resolution Lidar (HSRL)





- Laser tuned to I_2 absorption line
- Can also use interferometer
- Particulate backscatter blocked from “Molecular Channel”

High Spectral Resolution Lidar (HSRL)

- A ‘well-posed problem’: 2 measurement, 2 unknowns (b_{bp}, k_d)

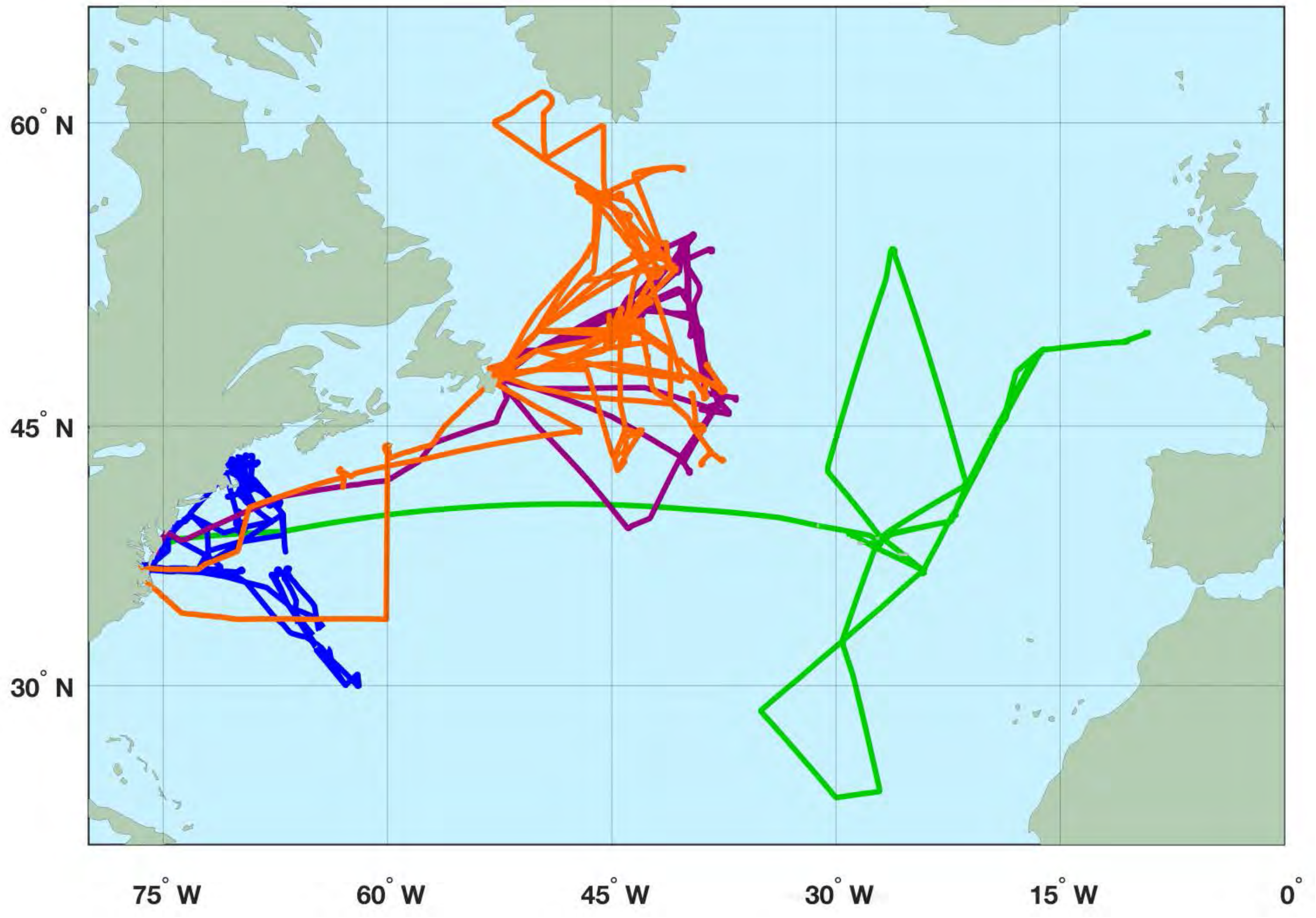
$$S_M(z) = \beta_M \exp\left[-2\int_0^z K_d(z')dz'\right](Atmos.Transmission)^2$$

$$S_P(z) = [\beta_P(z) + \beta_M] \exp\left[-2\int_0^z K_d(z')dz'\right](Atmos.Transmission)^2$$

$$K_d(z) = \left[-\frac{1}{2}\frac{d}{dz}\ln(S_M(z))\right]$$

$$\beta_P(z) = \beta_M \left[\frac{S_P(z)}{S_M(z)} - 1\right]$$

Ocean Retrievals with HSRL



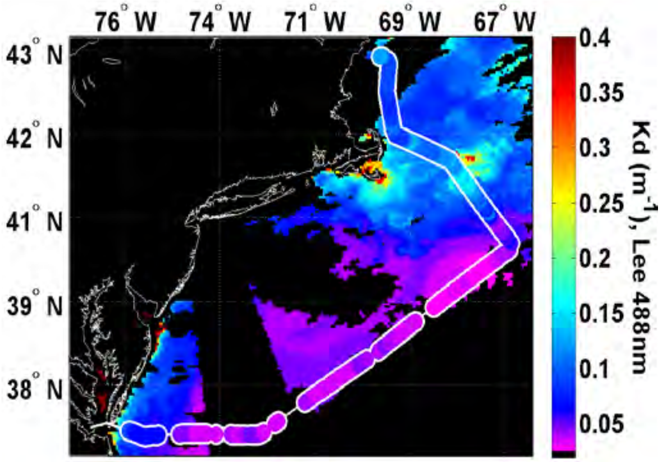
🟩 = 2012 Azores/AMT campaign

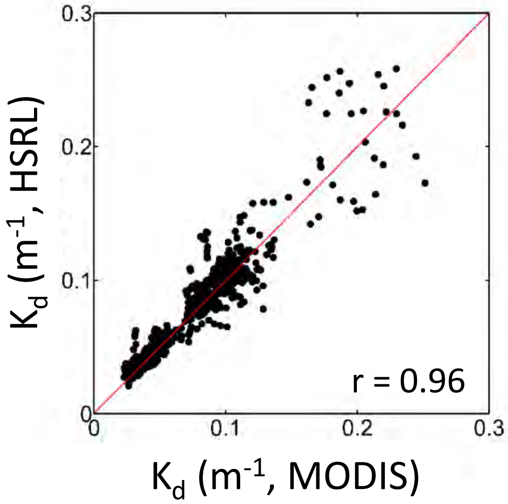
🟦 = 2014 NASA SABOR campaign

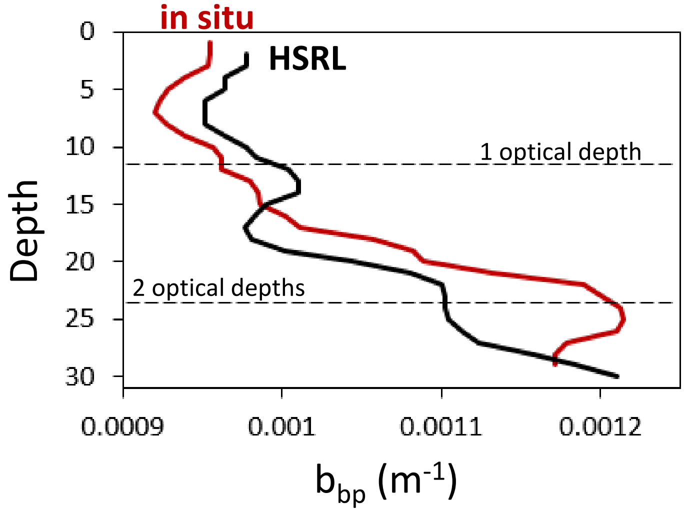
🟪 = 2015 NASA NAAMES 1 campaign

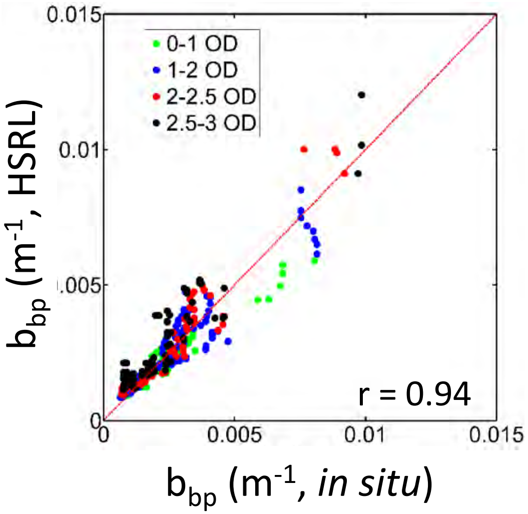
🟧 = 2016 NASA NAAMES 1 campaign

Ocean Retrievals with HSRL





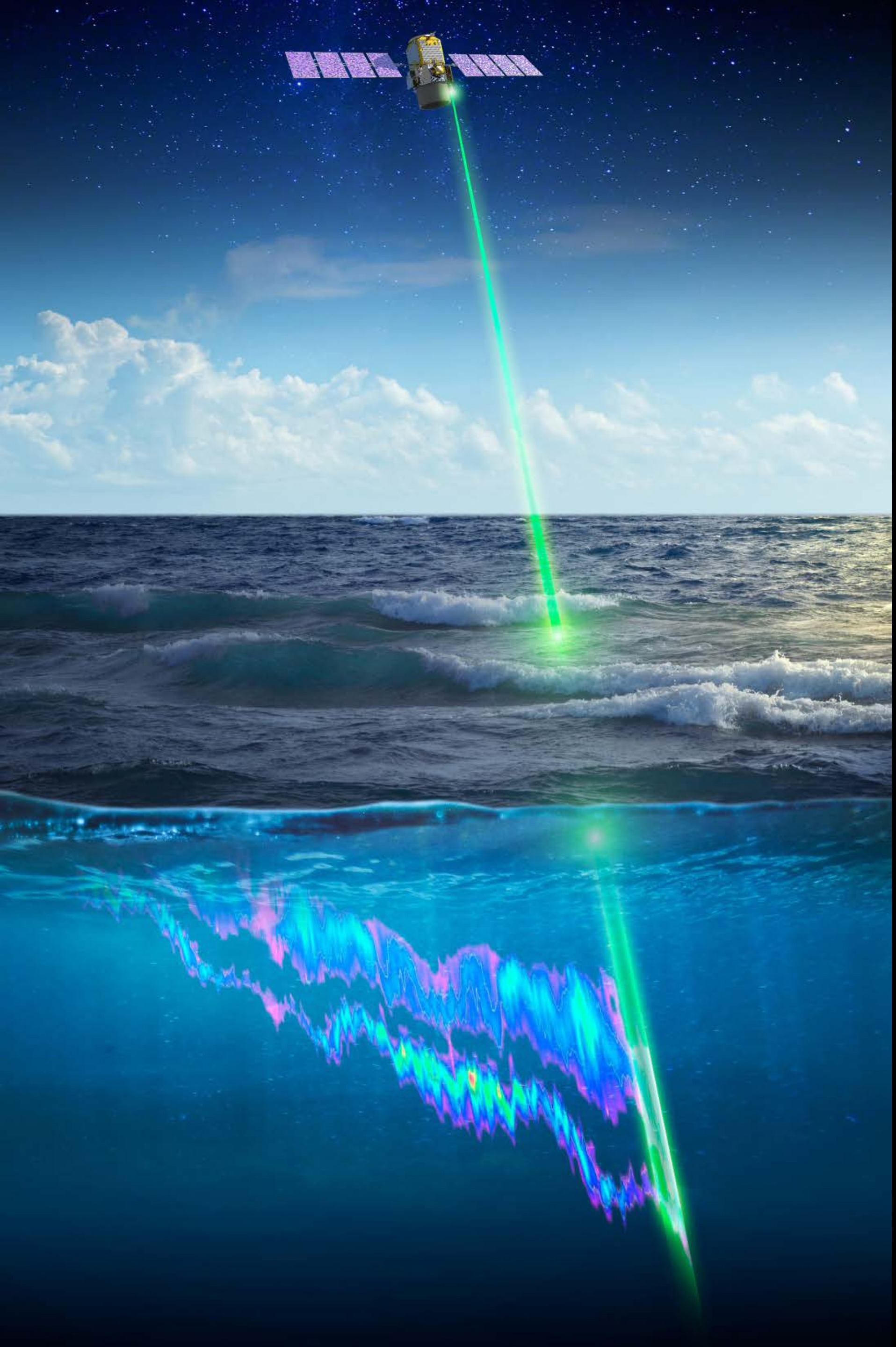




Key Points

- Accurate retrievals of b_{bp} and k_d
- Match-ups have spatial & temporal differences
- Accurate retrieval of vertical structure @ 1m resolution
- Water column profiling to ~3 optical depths
- Improvements in ΣNPP >50% for SABOR (other studies > 100%)

Data from John Hair (NASA LaRC) & *Schulien et al. 2017 Optics Express (in press)*



Looking ahead…

… it is time to think about what we can really do with a lidar mission actually designed for ocean retrievals

☐subsurface data courtesy of Jim Churnside

An Ocean-optimized Lidar

Shopping list additions to CALIOP (1064 ∥ / 532 ∥ / 532 ⊥ / 22 m)

	Capability	**Value to Ocean Science**
CALIOP Plus	<3-m vertical resolution	• Profiles of K_d, b_{bp} , & geophysical properties (C_{phyto}, POC, NPP) • Calibration error • K_d- b_{bp} separation error (need ocean color or optical model)
Plus	HSRL at 532 nm Depolarization at 1064 nm	• Calibrated through profile • Well-posed retrieval of b_{bp} & K_d • Improved geophysical products • Independent of ocean color and optical modeling
Plus	Chl Fluorescence	• Chlorophyll concentration (night) • Nonphotochemical Quenching • Iron stress
Plus	HSRL at 355 nm Depolarization at 355 nm	• Accurate independent profiles of b_{bp} & K_d at 532 and 355 nm • Separation of CDOM & pigments • Slope of particle size distribution • Improved vertically-resolved NPP

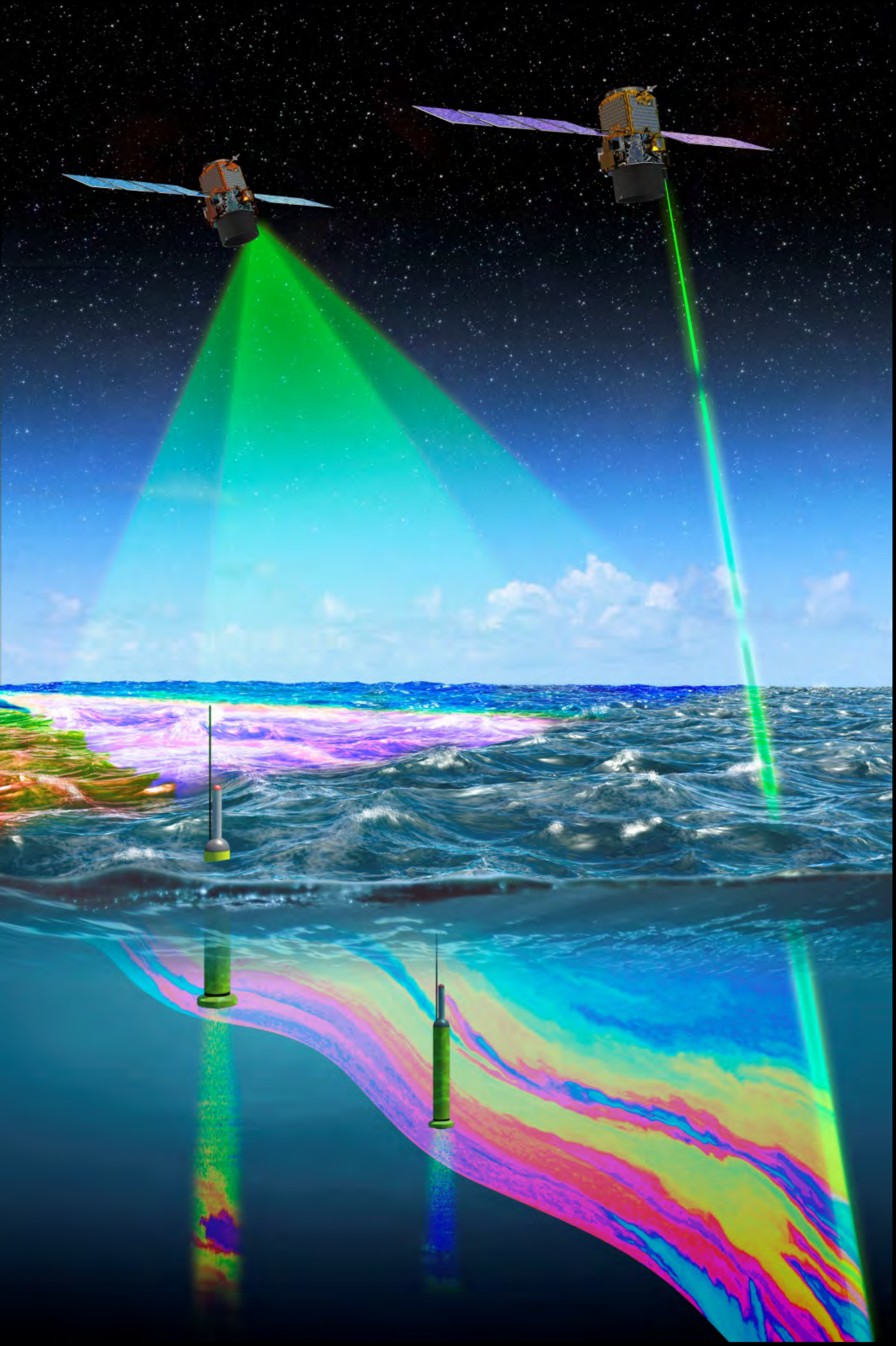
Entry requirement for ocean research

Minimal additional cost to mission

An Ocean-optimized Lidar

1. Better understanding of polar / other problematic regions
2. Major improvements in water column phytoplankton stocks (e.g., biomass) and rates (e.g., primary production)
3. Globally representative data for ocean color algorithm development
4. New information on physiology (e.g., iron stress, photoprotection)
5. Ecological insights from day-night stock changes
6. More accurate ocean color atmospheric corrections
7. Active mixing depth of the ocean surface layer

& much more…



Future Constellation

Enabling a 3-dimensional reconstruction of global ocean ecosystems by combining strengths of different approaches

- Optimized ocean-atmosphere lidar
- Advanced ocean color sensor
- Scanning Polarimeter
- Bio-Geo-Argo global array

Achievable in near future (PACE)

MESCAL (Monitoring the Evolving State of Clouds and Aerosol Layers)

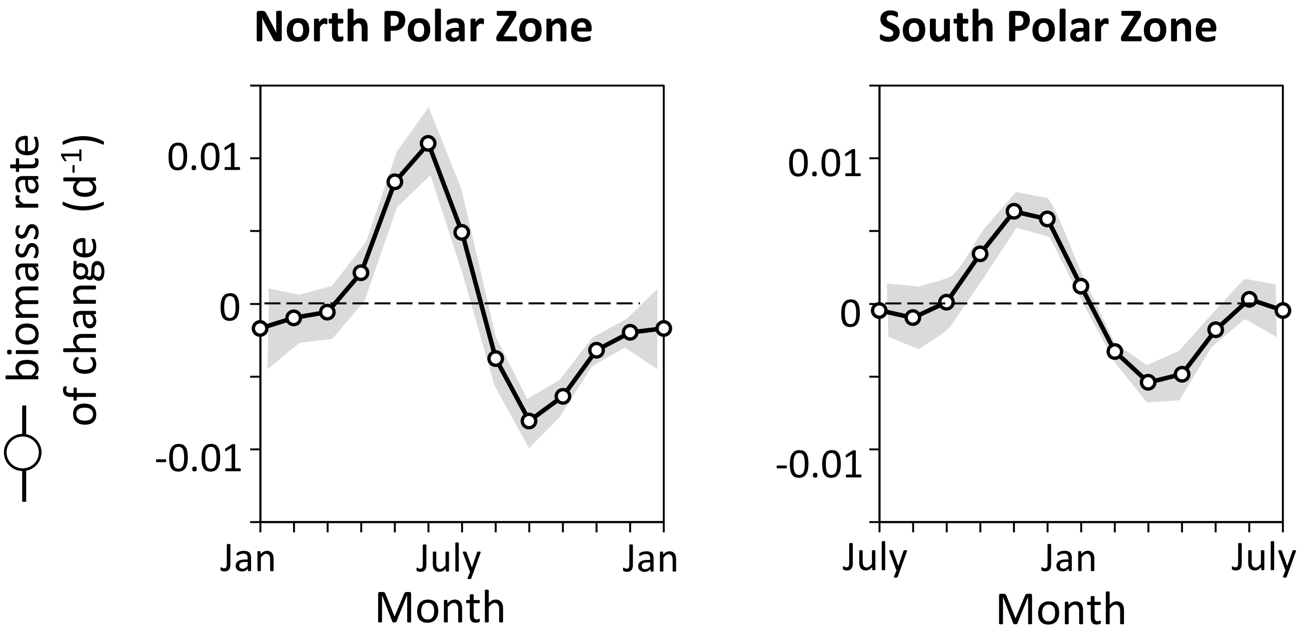
- *CNES concept study partnering with NASA LaRC*

THANK YOU

Chris Hostetler
Yongxian Hu
Johnathan Hair
Jennifer Schulien
Emmanuel Boss
David Siegel
Jorge Sarmiento
Giorgio Dall’Olmo
Sharon Rodier
Charles Trepte
Xiaomei Lu
Amy Jo Scarino
Robert O’Malley

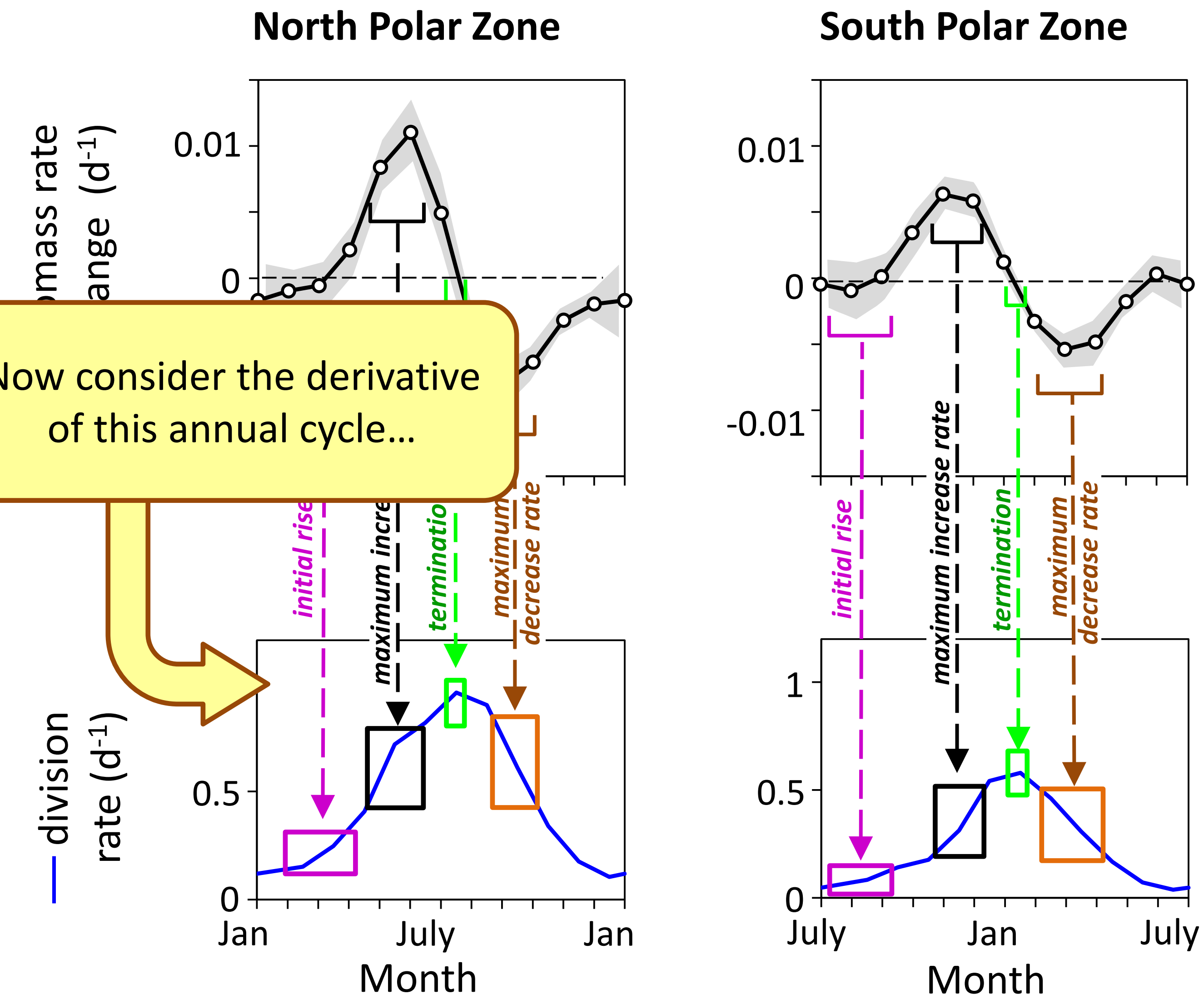
NASA Ocean Biology and Biogeochemistry Program
NASA Earth Science Technology Office
NASA Airborne Instrument Technology Transition Program

Polar Biomass Dynamics



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

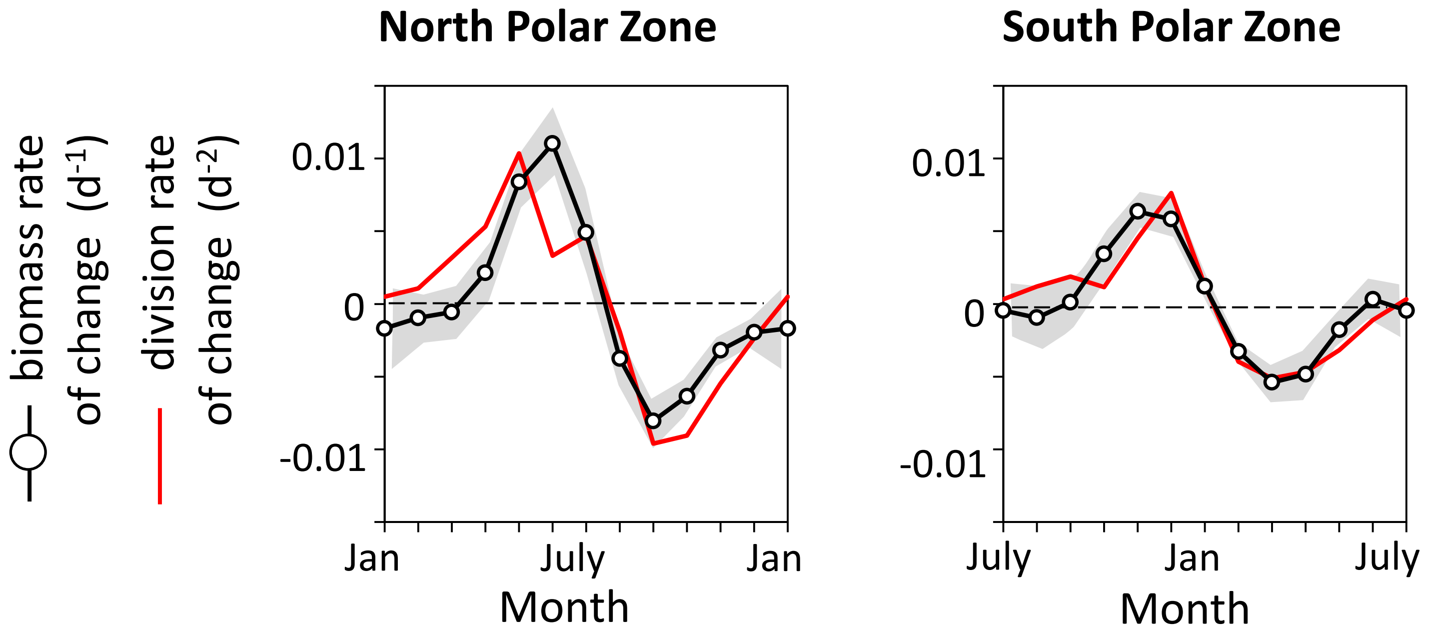
Polar Biomass Dynamics



Now consider the derivative of this annual cycle…

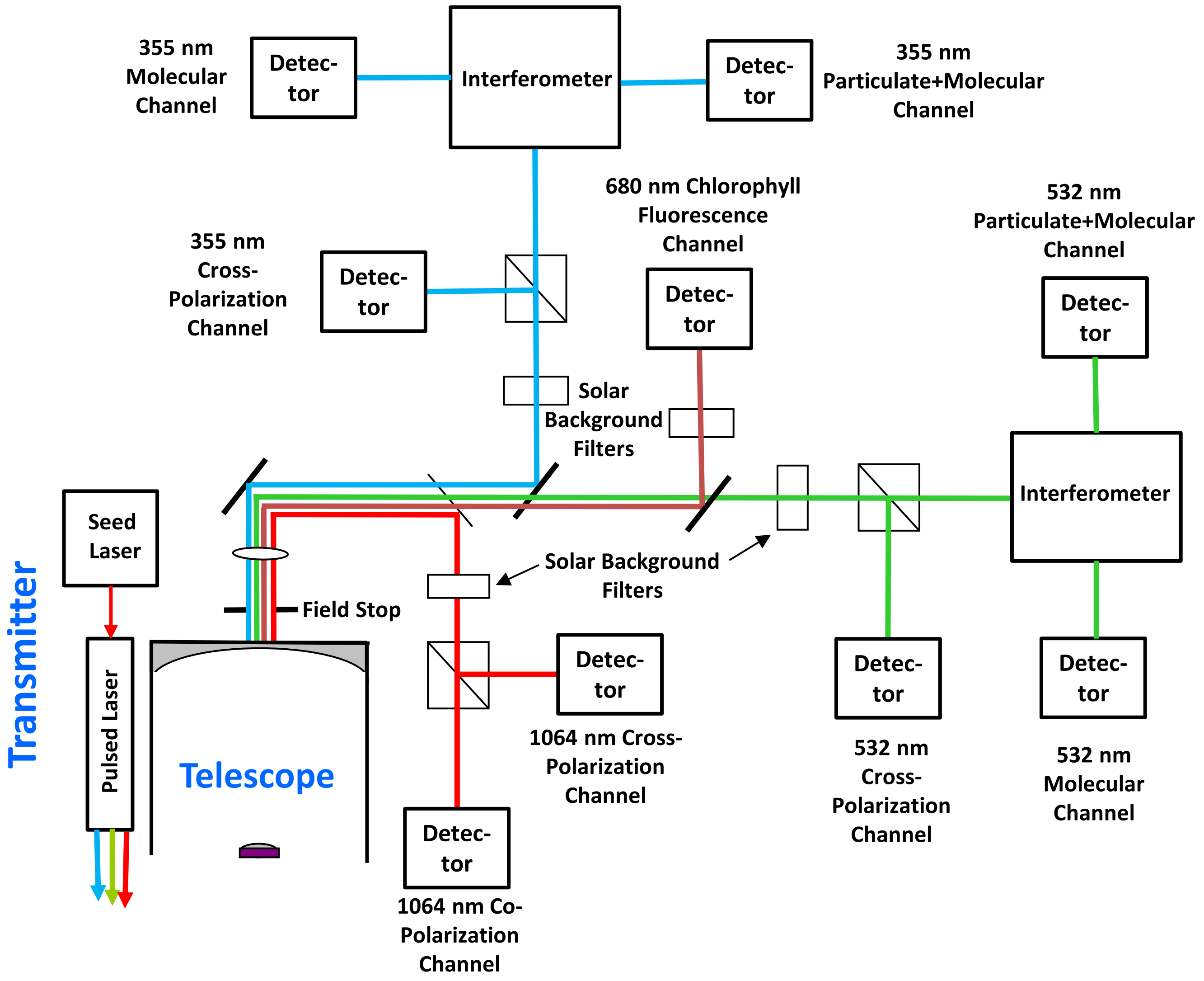
Behrenfeld et al. 2016 Nature Geoscience 19, 118-122

Polar Biomass Dynamics

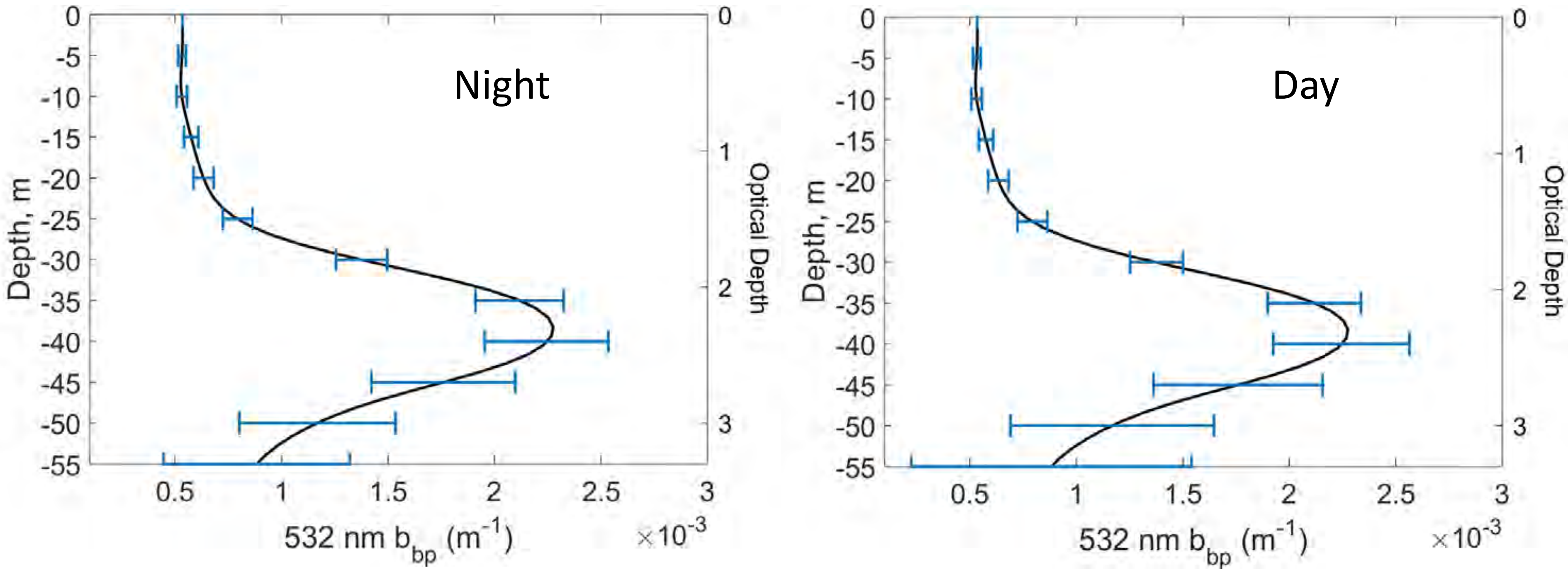


The temporal lag in predator (zooplankton, viruses, etc) responses to phytoplankton division rate changes causes the annual cycle in biomass to track accelerations and decelerations in division rate

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

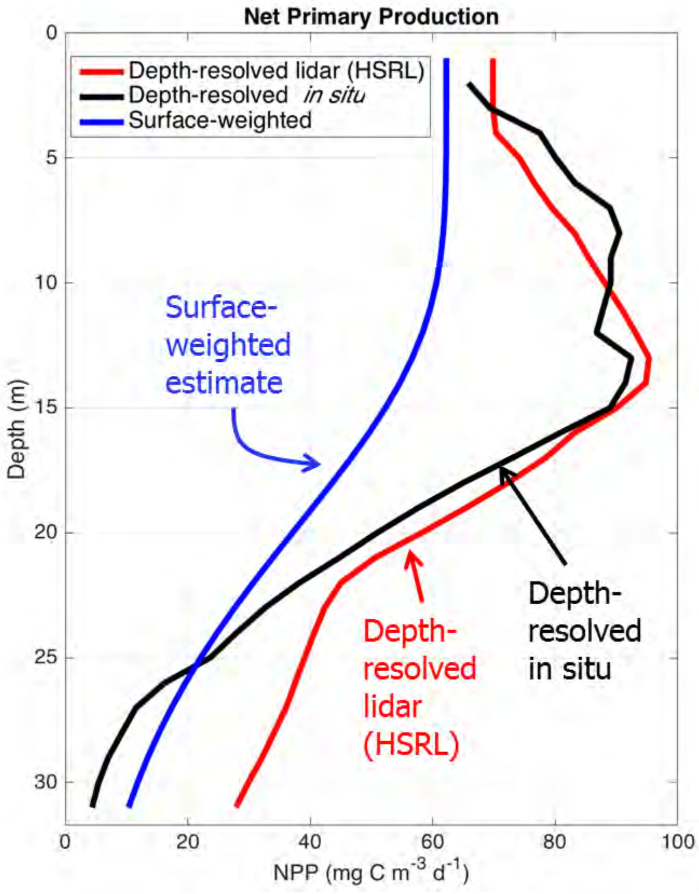

355 nm Molecular Channel
Detec-tor
Interferometer
Detec-tor
355 nm Particulate+Molecular Channel
680 nm Chlorophyll Fluorescence Channel
532 nm Particulate+Molecular Channel
355 nm Cross-Polarization Channel
Detec-tor
Detec-tor
Detec-tor
Solar Background Filters
Seed Laser
Interferometer
Transmitter
Solar Background Filters
Field Stop
Pulsed Laser
Telescope
Detec-tor
1064 nm Cross-Polarization Channel
Detec-tor
532 nm Cross-Polarization Channel
Detec-tor
532 nm Molecular Channel
Detec-tor
1064 nm Co-Polarization Channel

Spaceborne HSRL profiling possible to 3 optical depths



- Simulated profiling through 70% of the euphotic zone possible with a realizable system
  - 150 mJ at 140 Hz at 532 nm
  - 1.5 m telescope (similar to ADM-Aeolus)
  - Altitude 450 km for these simulations
- Resolution/precision can be increased via changes in instrument parameters

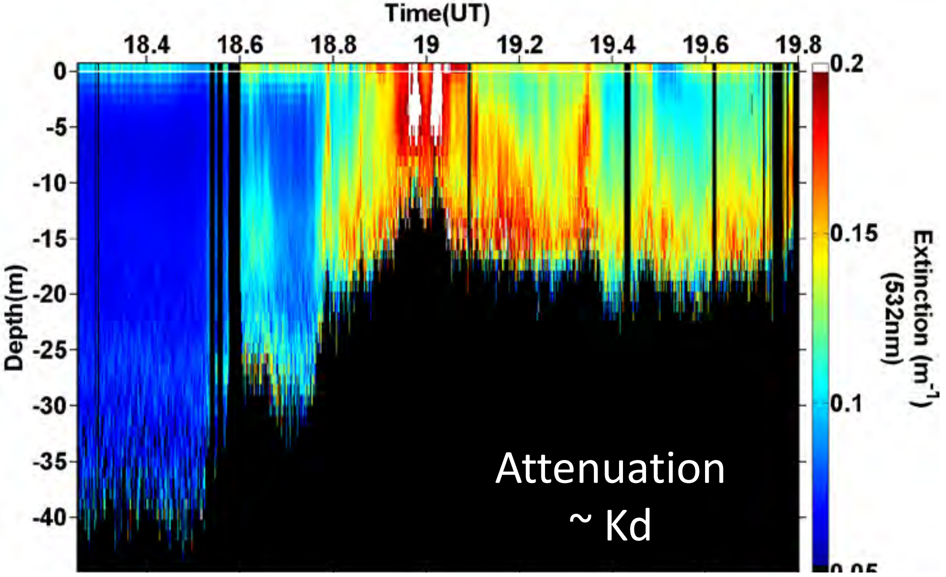
Why do we care about depth-resolved profiles?



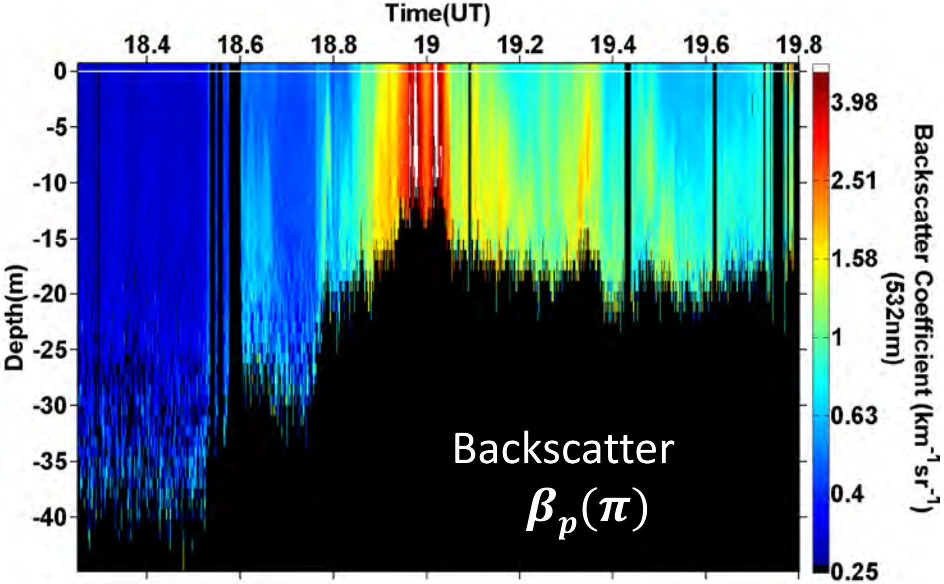
- Data from the SABOR mission off East Coast US (2104) demonstrating differences between surface-weighted and depth resolved profiles using in situ and HSRL lidar data.
  - Ocean color style estimates off by as much as 54%
  - Errors can be much larger in other parts of the ocean

Modified from Schulien et al., **Vertically- resolved phytoplankton carbon and net primary production from a High Spectral Resolution Lidar**, submitted March 2017.

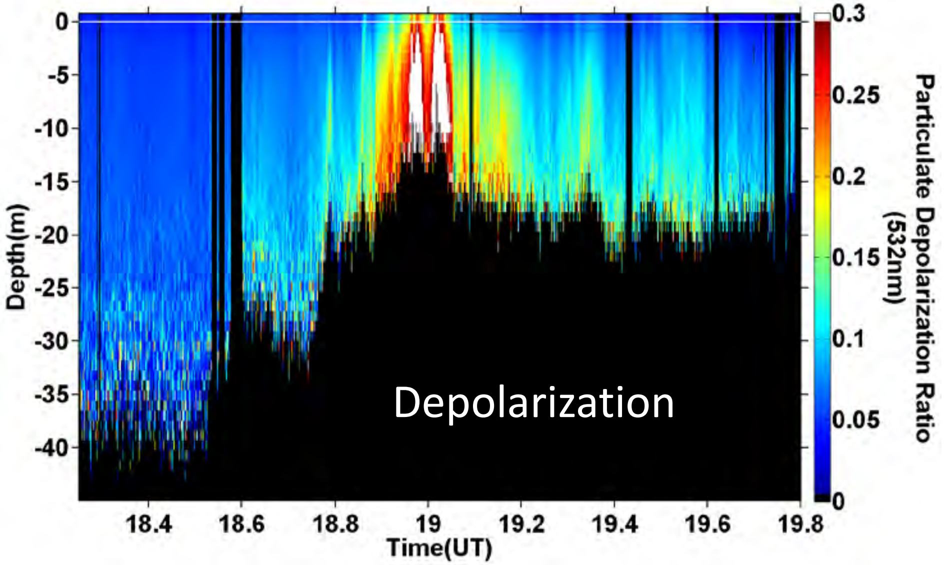
Four ocean products from HSRL-1



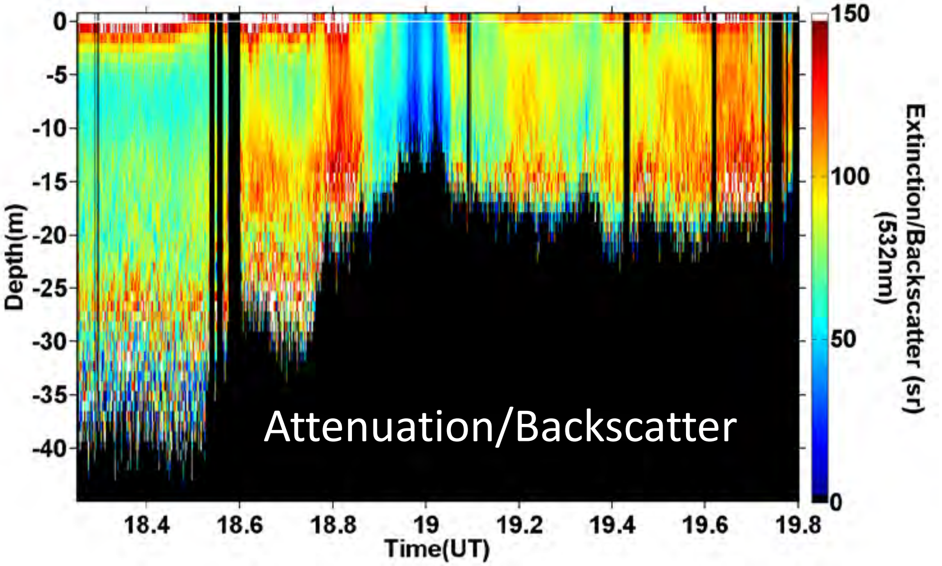
Attenuation ~ Kd



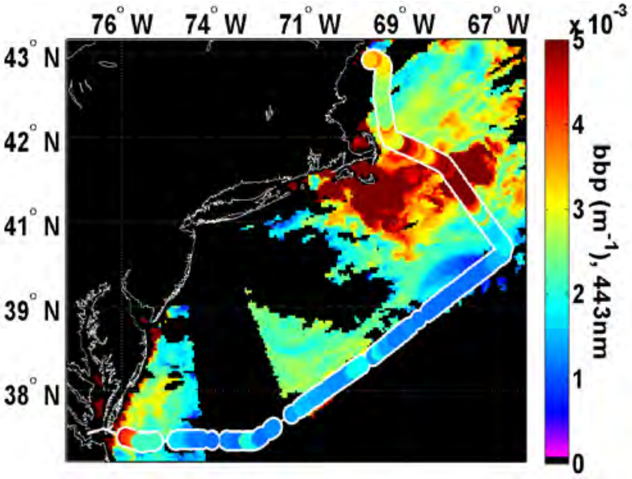
Backscatter $\beta_p(\pi)$



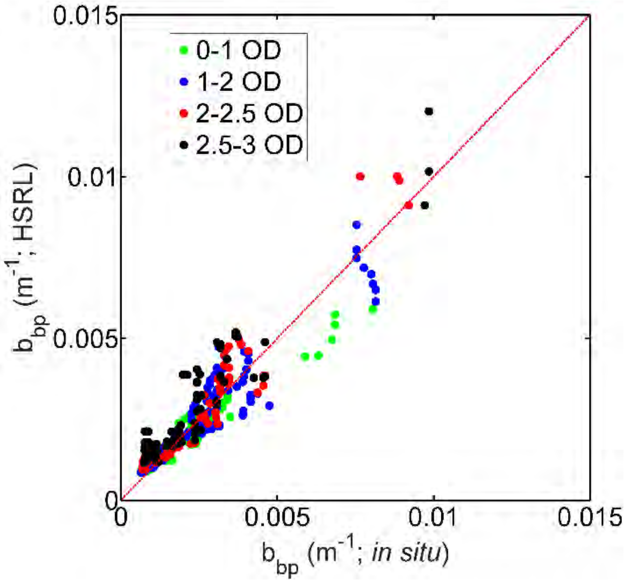
Depolarization



Attenuation/Backscatter

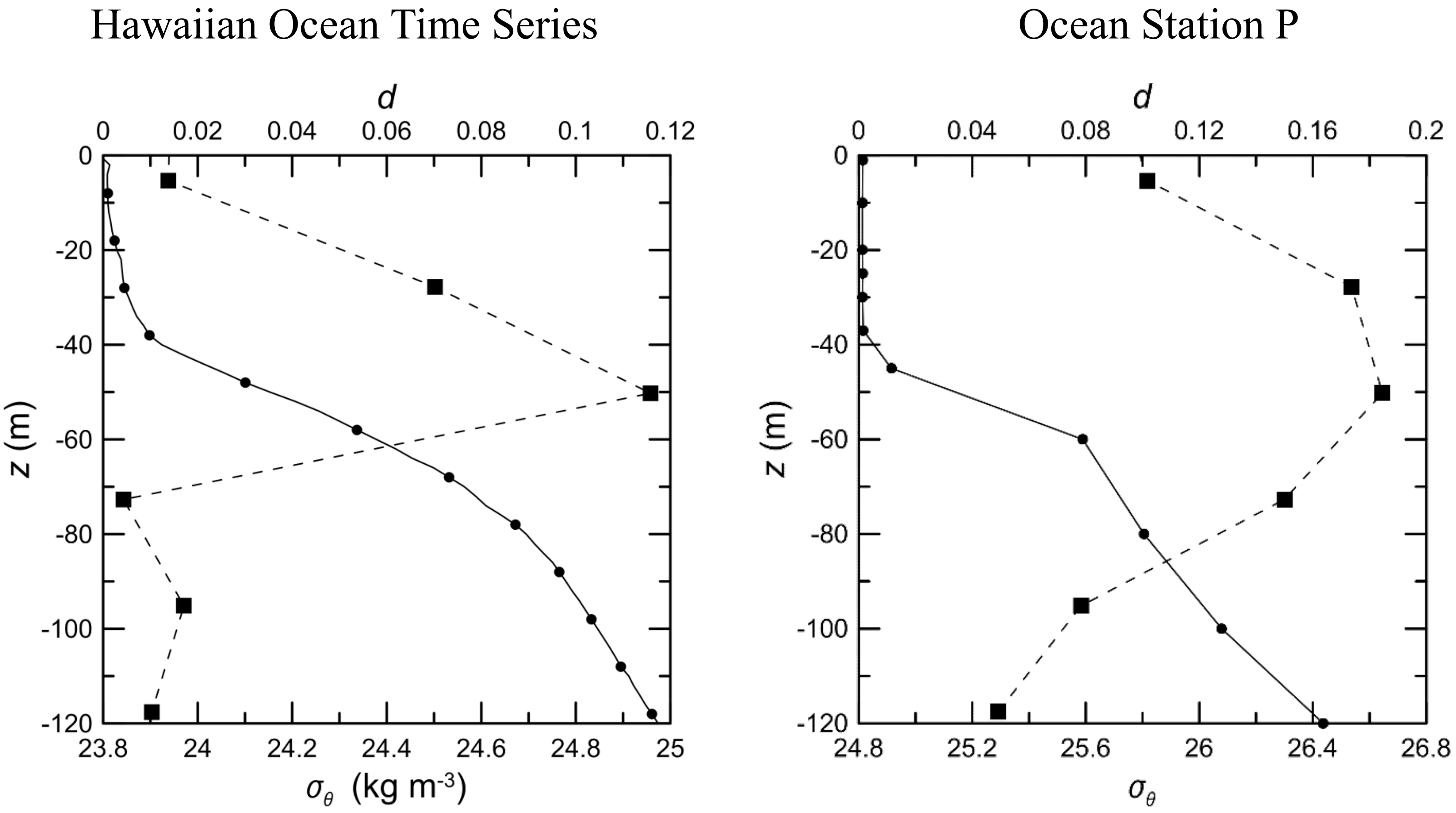


76° W
74° W
71° W
69° W
67° W
43° N
42° N
41° N
39° N
38° N
x 10^-3
5
4
3
2
1
0
bbp (m^-1), 443nm



0.015
0.01
0.005
0
b_bp (m^-1; HSRL)
b_bp (m^-1; in situ)
● 0-1 OD
● 1-2 OD
● 2-2.5 OD
● 2.5-3 OD

Churnside

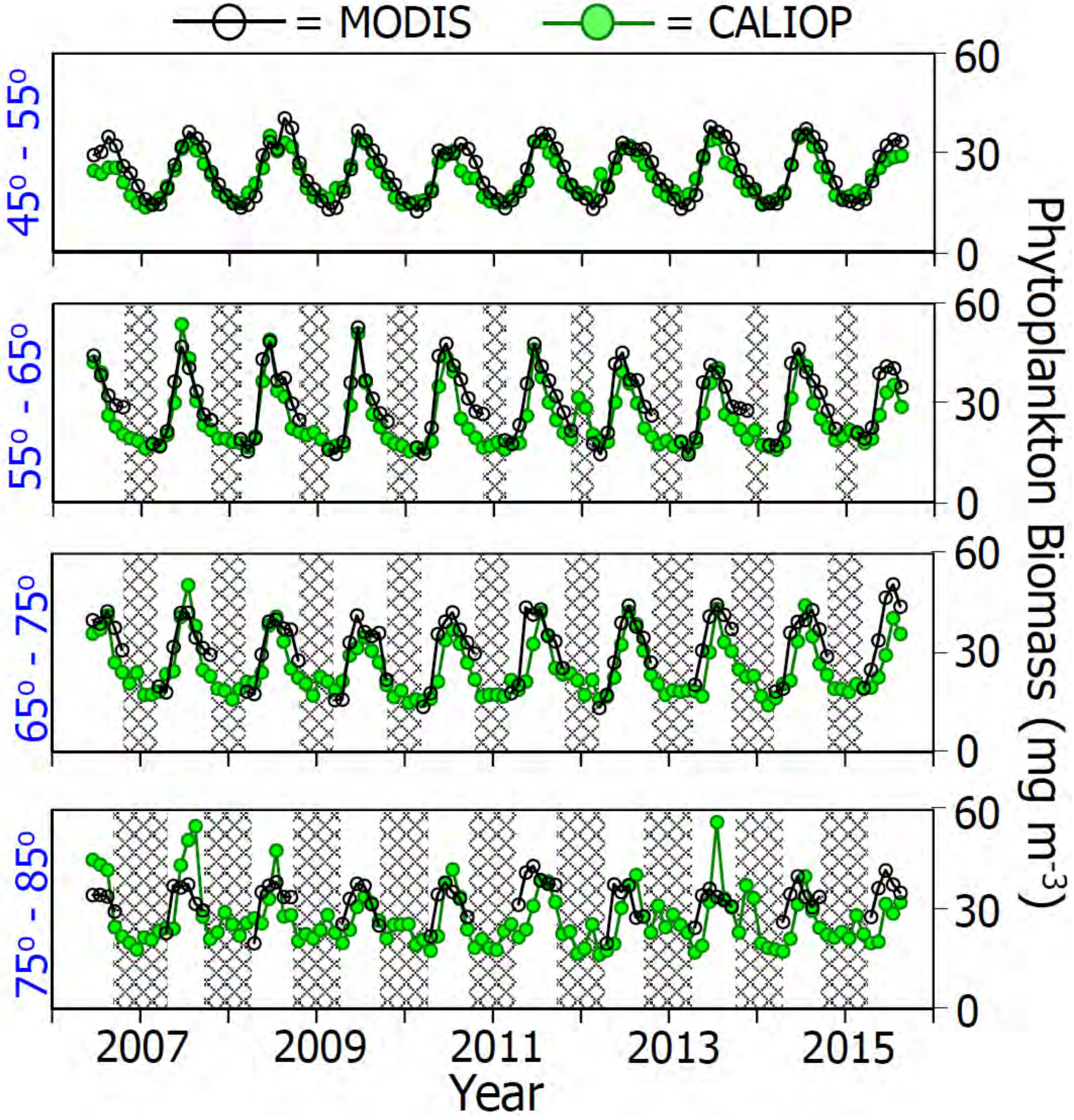


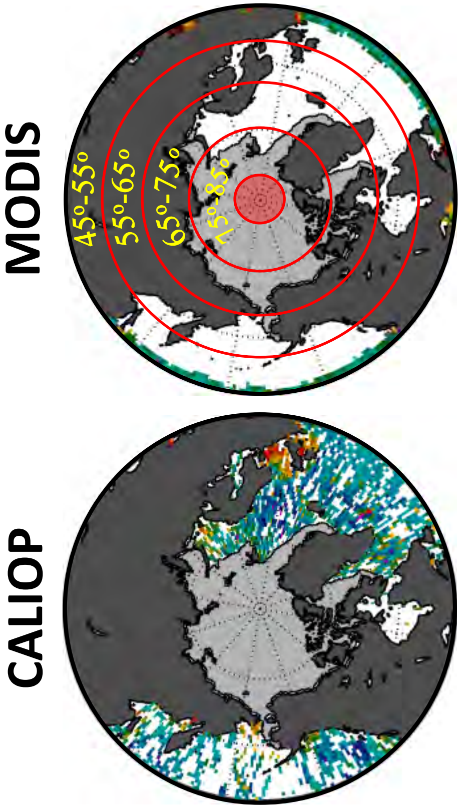
Hawaiian Ocean Time Series

Ocean Station P

Profiles of density σ_θ (solid line) and lidar depolarization *d* (dashed line).

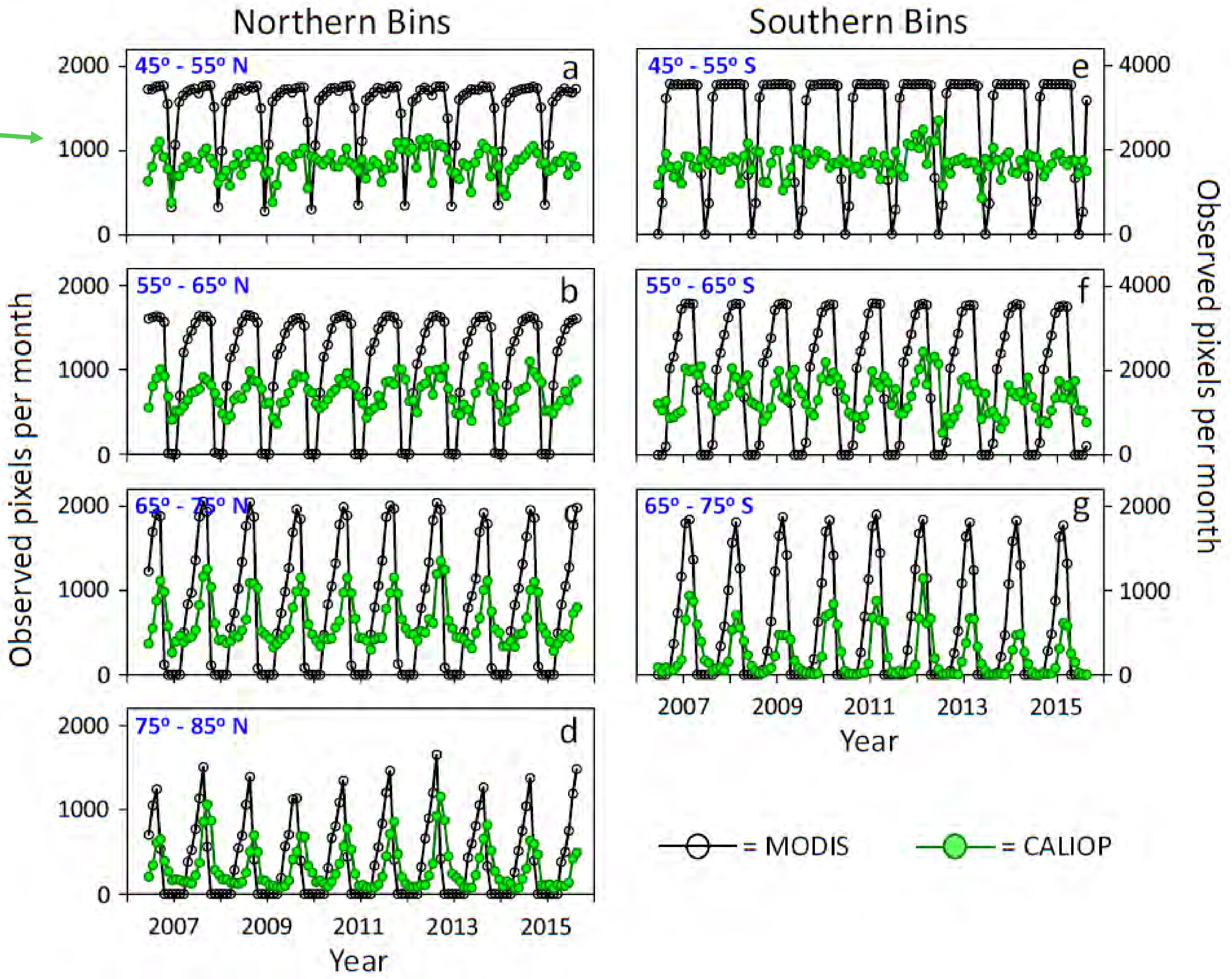
Lidar (CALIPSO) depolarization after averaging over 100 shots, 33 km and in-situ density profiles.


= MODIS
= CALIOP
45° - 55°
55° - 65°
65° - 75°
75° - 85°
60
30
0
Phytoplankton Biomass (mg m^{-3})
2007
2009
2011
2013
2015
Year

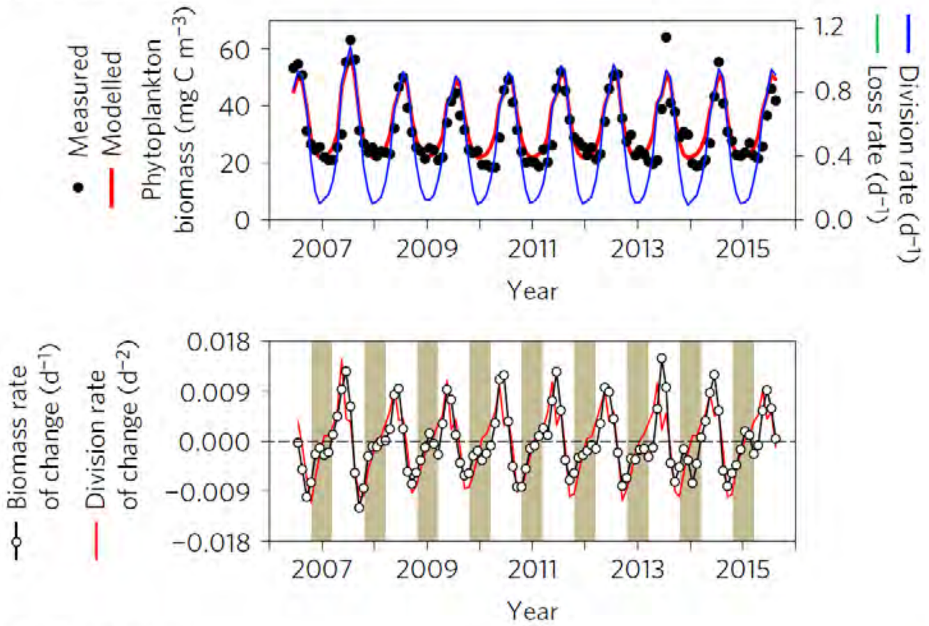

MODIS
CALIOP
45°-55°
55°-65°
65°-75°
75°-85°

1˚x 1˚ latitude bins with valid b_{bp} ret

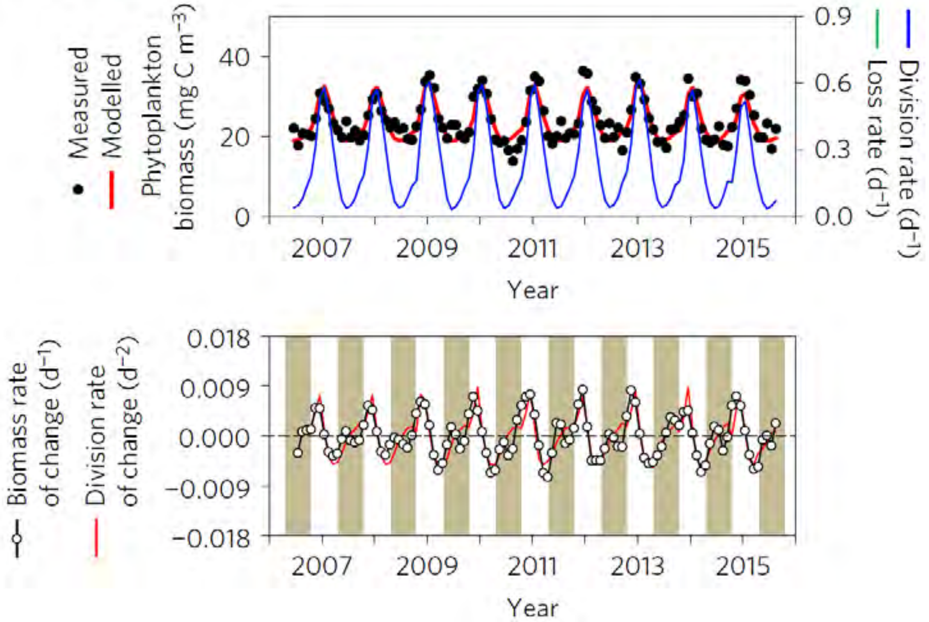
70% is theoretical max percentage of MODIS pixels sampled by CALIOP

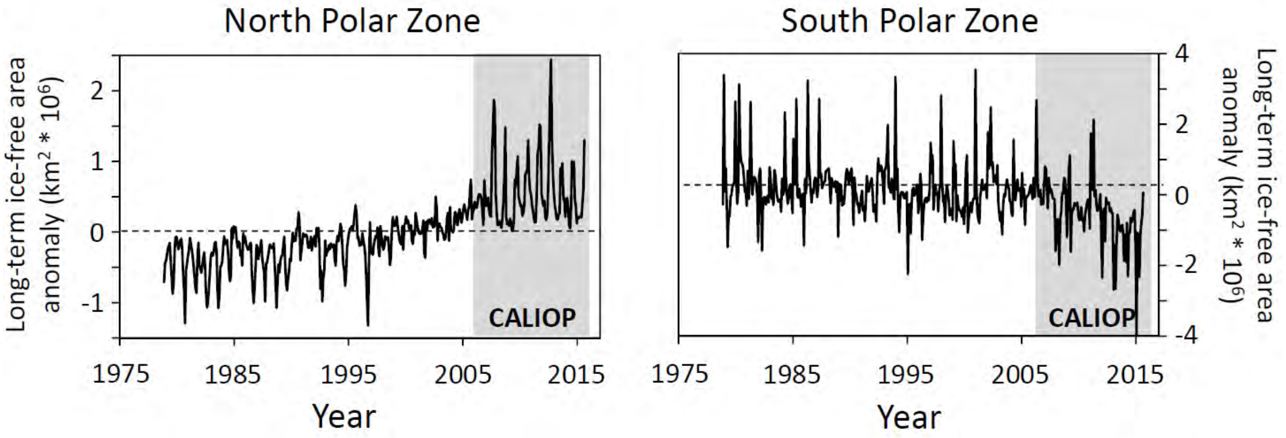


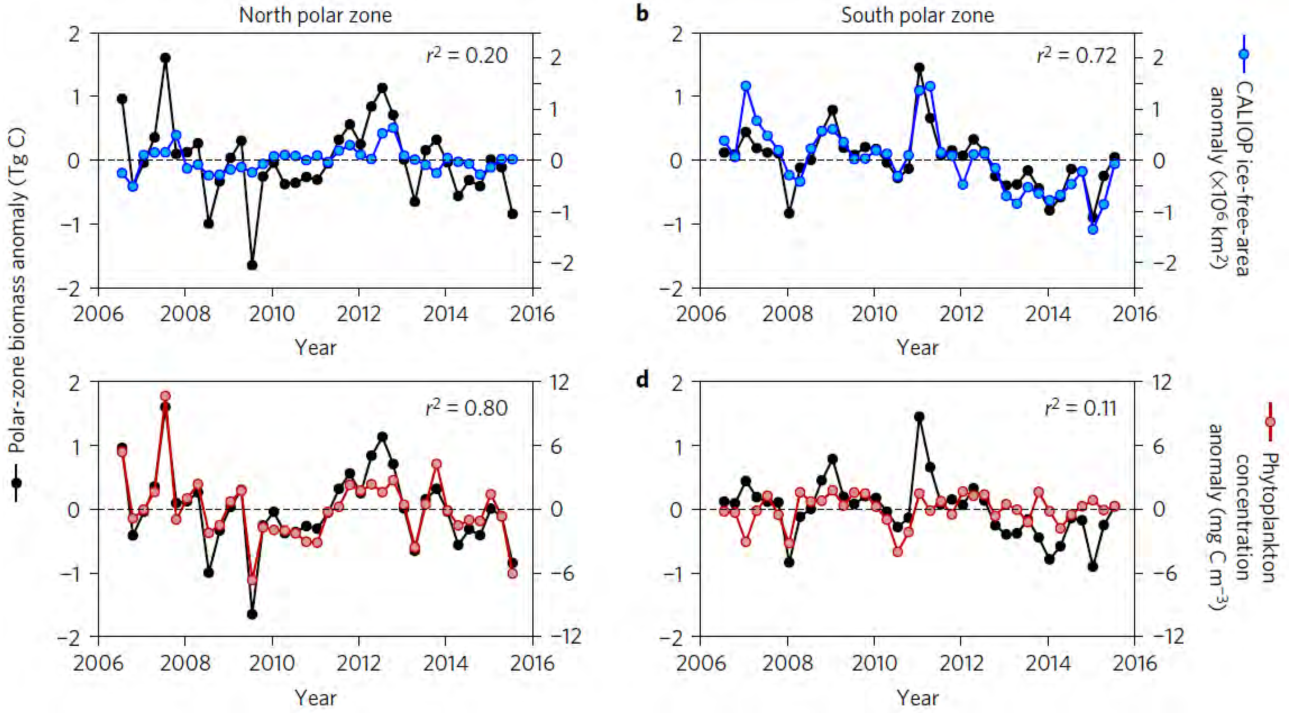
North polar zone



South polar zone




North Polar Zone
South Polar Zone
Long-term ice-free area anomaly (km^2 * 10^6)
2
1
0
-1
4
2
0
-2
-4
CALIOP
CALIOP
1975
1985
1995
2005
2015
Year
Year


North polar zone
b
South polar zone
r^2 = 0.20
r^2 = 0.72
d
r^2 = 0.80
r^2 = 0.11
Polar-zone biomass anomaly (Tg C)
CALIOP ice-free-area anomaly (×10^6 km^2)
Phytoplankton concentration anomaly (mg C m^{-3})
2
1
0
−1
−2
12
6
0
−6
−12
2006
2008
2010
2012
2014
2016
Year