Ocean and atmospheric boundary layer measurements from space based lidars

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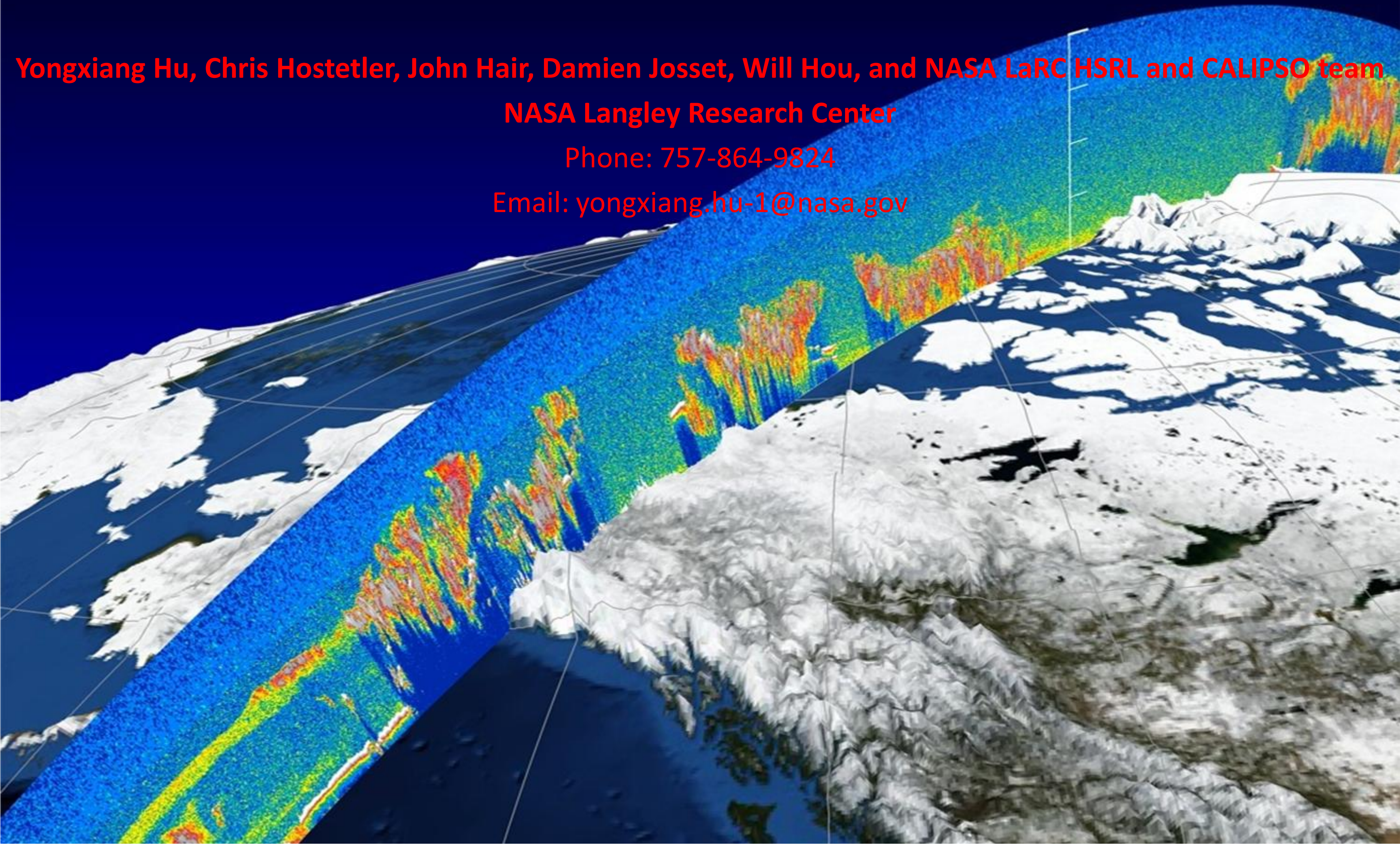


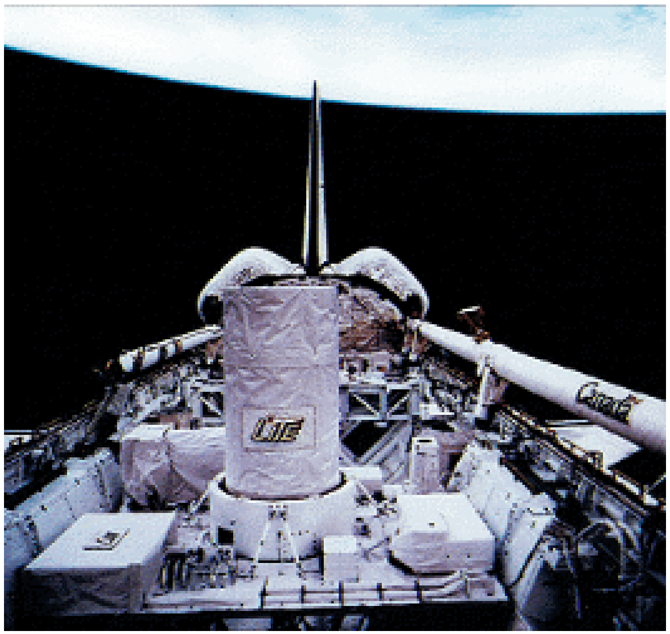
Outline of the talk

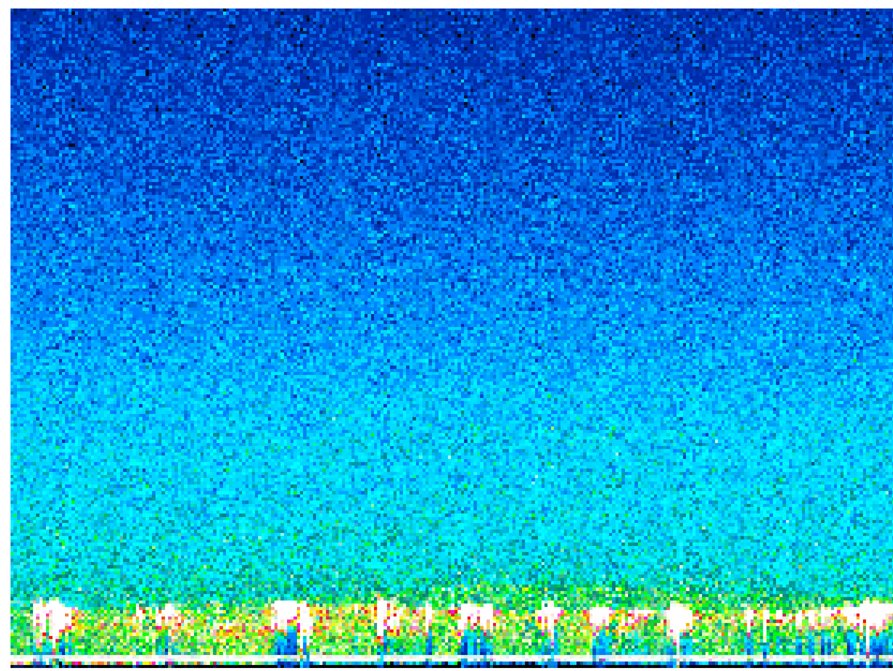
- CALIPSO measurements
  1. atmospheric boundary layer,
  2. ocean surface
  3. ocean sub

- High Spectral Resolution Lidar and Potential lidar measurements for the decadal survey mission

- Lidar for cubesate under-development
  1. aa-train measurements of cloud 3D structure
  2. ONR ocean lidar for turbulence profiling

First lidar in space: LITE experiment on Space Shuttle (1994)

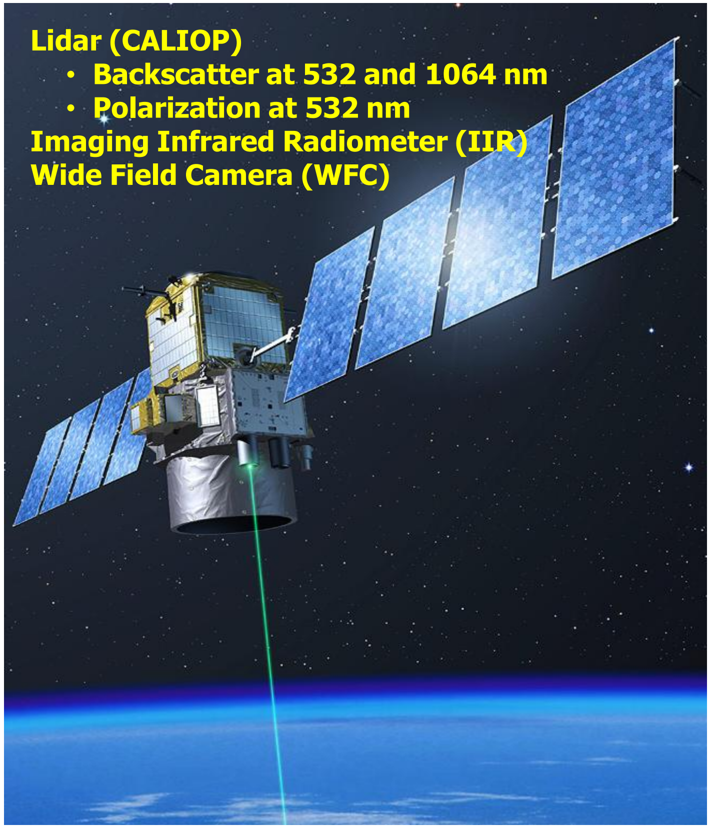




LITE provided the first global observations of boundary layer height. .

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) (2006 – 2020?): first satellite mission with profiling lidar

- 12 years of operations in the A-train constellation
- Designed for measurements of 3D distributions of aerosols and clouds
  - vertical resolution: 30 m
- ocean properties from CALIOP data
  - Sea-surface wind speed
  - Particulate backscatter (b_{bp}) enabling estimates of
    - Particulate organic carbon (POC)
    - Phytoplankton biomass (C_{phyto})



CALIPSO website: www-calipso.larc.nasa.gov

CALIPSO Payload
Three Near Nadir Viewing Instruments

Lidar

CALIOP

Cloud-Aerosol Lidar with Orthogonal Polarization

Vertical profiles of atmosphere

2 wavelength polarization sensitive lidar:

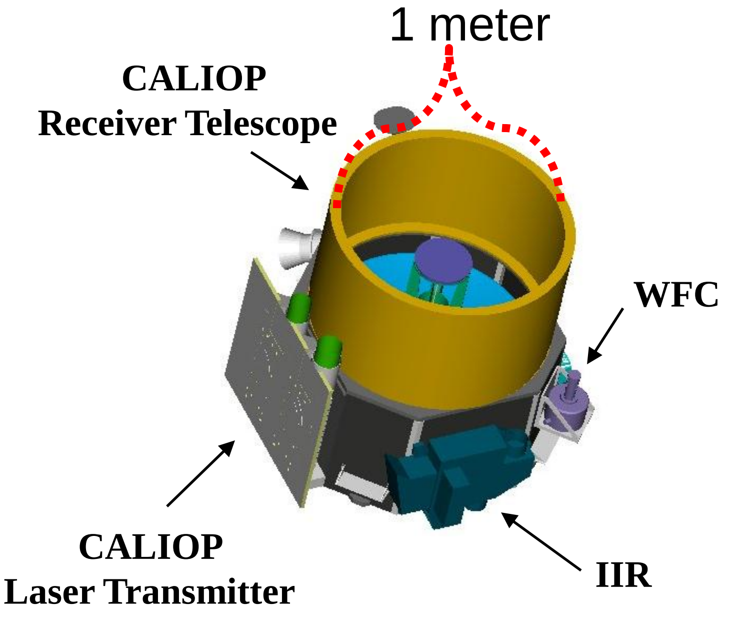
1064 nm, 532 nm (parallel and perpendicular)

Imaging Infrared Radiometer (IIR)

High-resolution image (swath product)

Wide Field Camera (WFC)

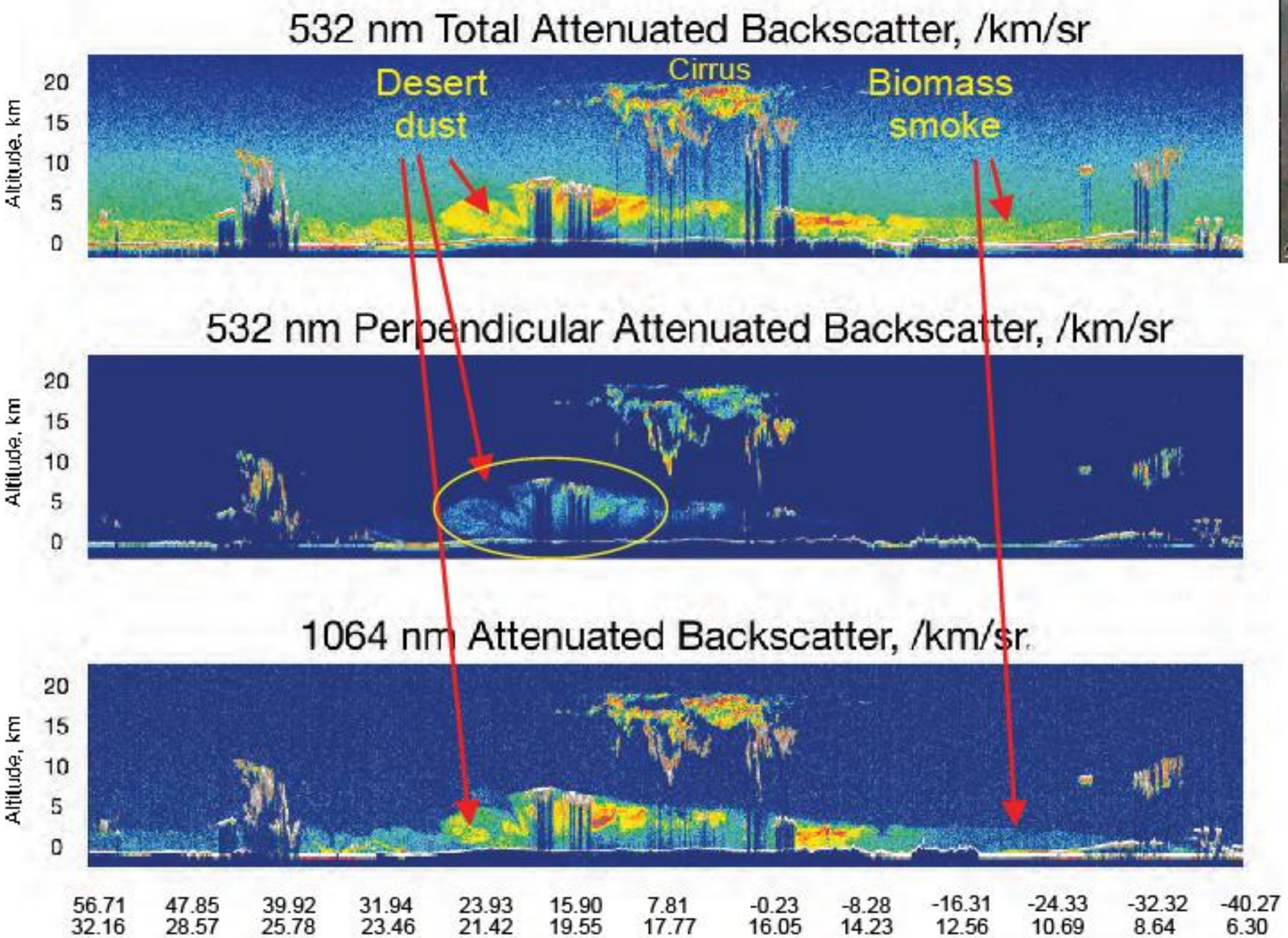
High-resolution image (125m resolution)

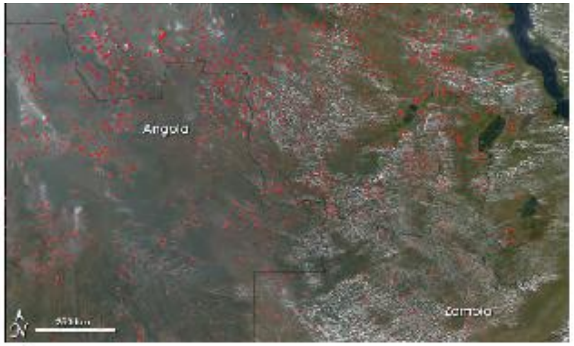


CALIPSO Payload

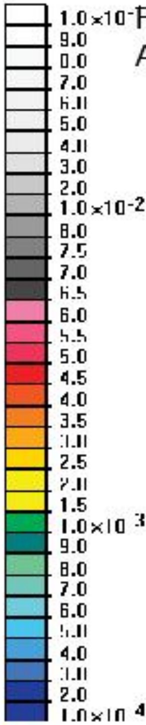
CALIPSO's primary mission: cloud and aerosol studies

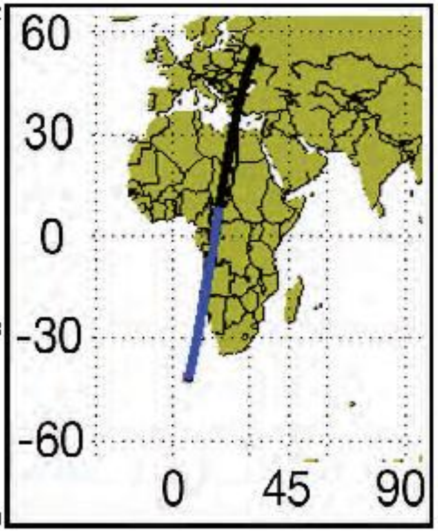
June 9, 2006



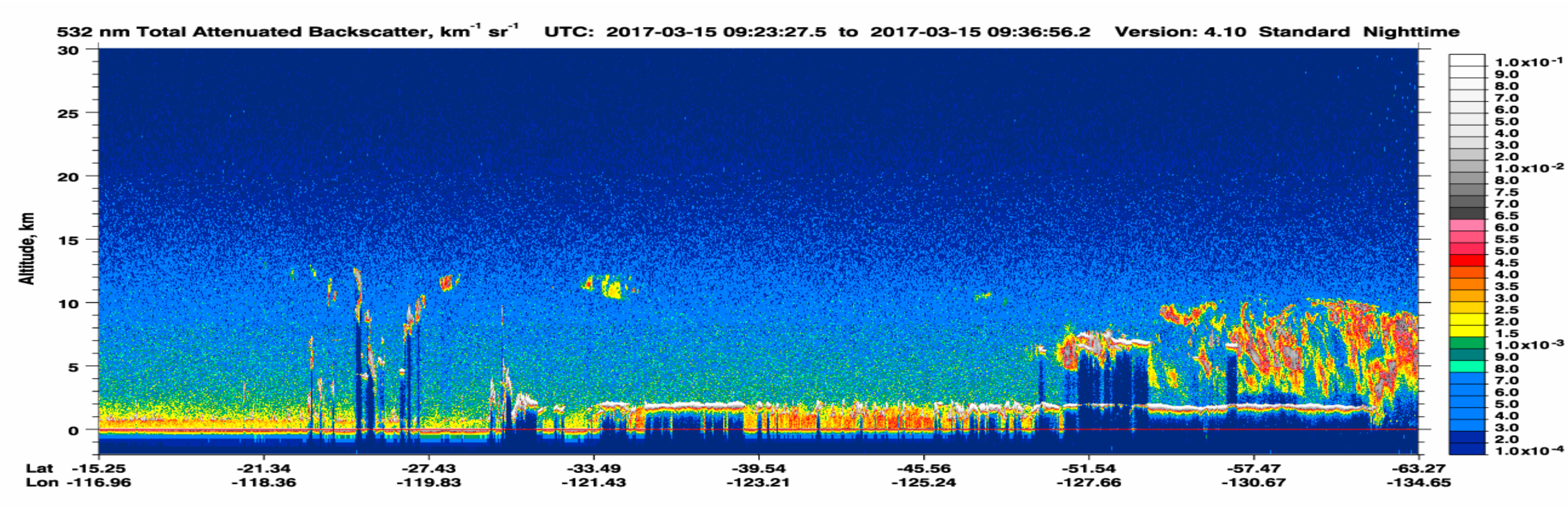


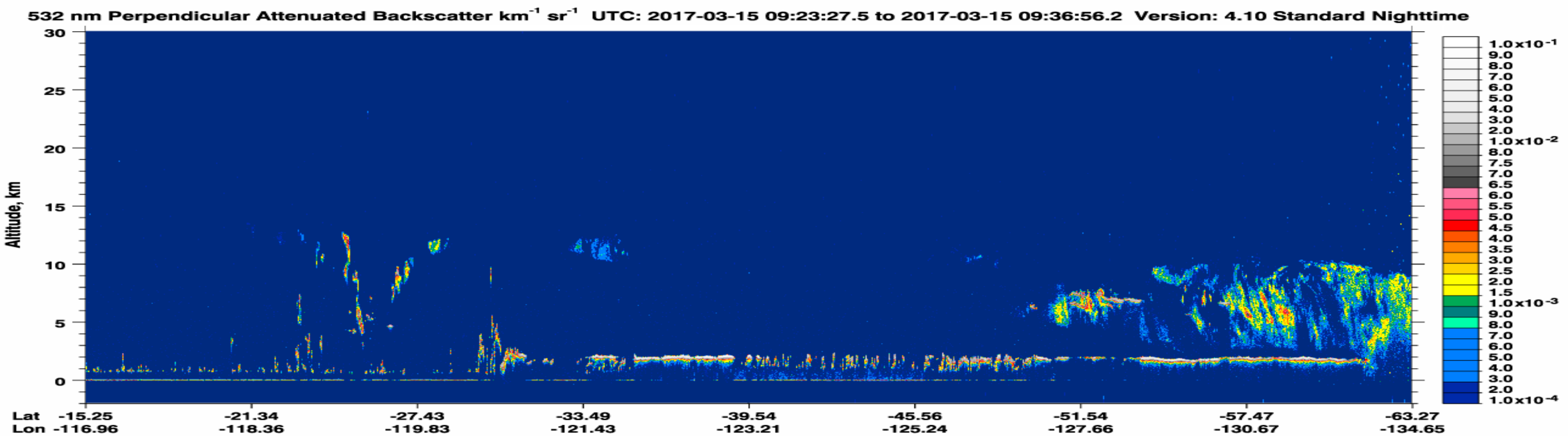
Fire locations in southern Africa from MODIS, 6/10/06





CALIPSO measurements of clouds and aerosols in the boundary layer





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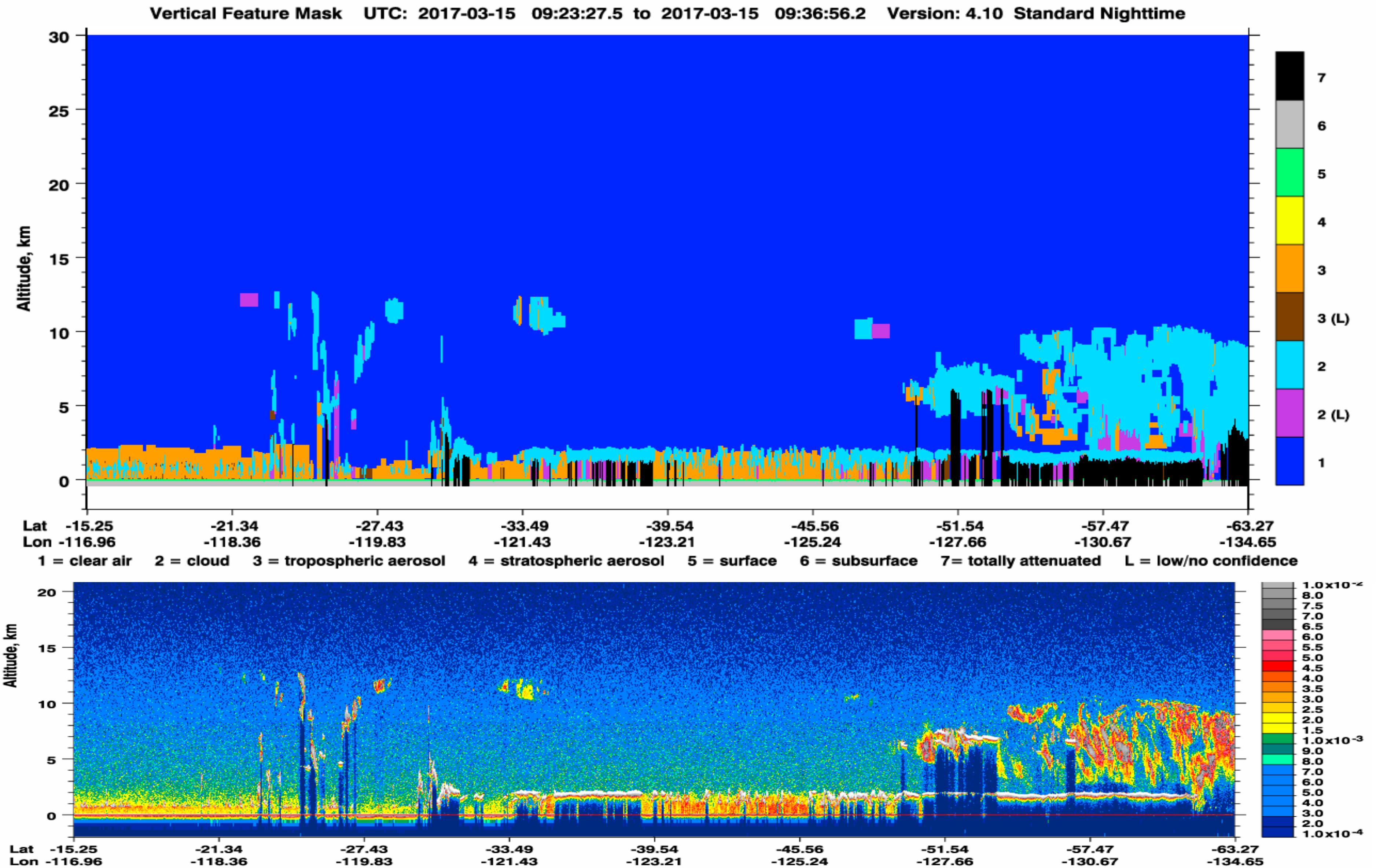
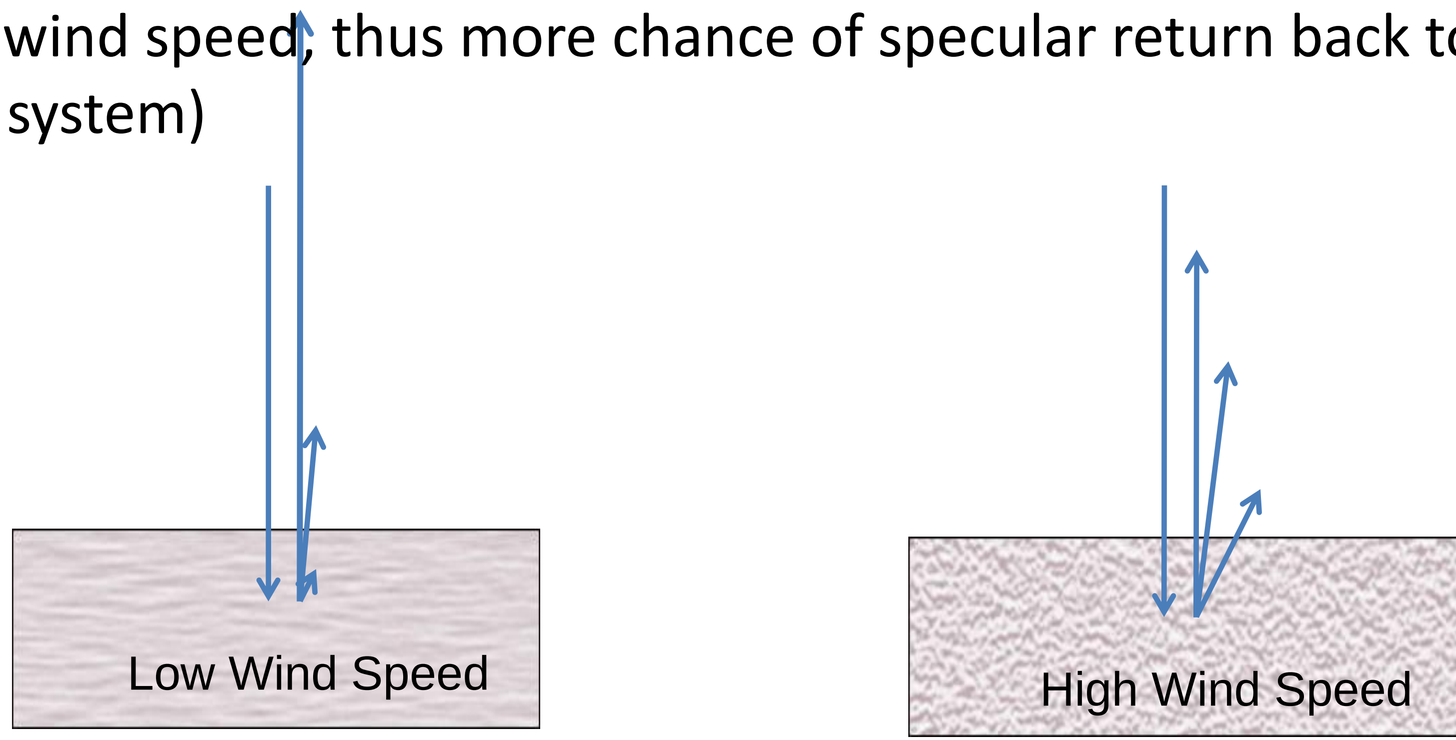


Deriving Sea surface wind speed from CALIPSO:

- The signal: ocean surface lidar backscatter signal from specular reflection
- The physics: higher wind → rougher surface → lower backscatter

  (nadir pointing laser; 2% sea surface reflection at 1064nm wavelength; higher probability of laser beam normal to sea surface at lower wind speed, thus more chance of specular return back to the lidar system)

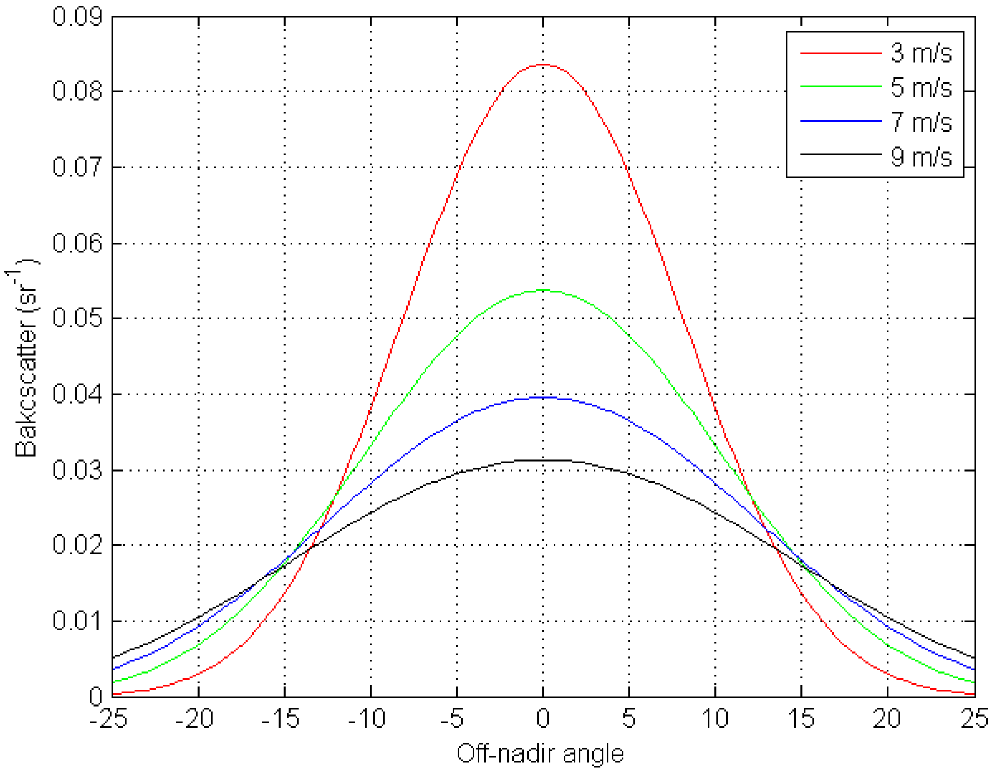


Mean square wave slope (*and wind speed*) is inversely proportional to CALIPSO lidar backscatter of ocean surface

Sea surface lidar backscatter (after a few corrections) = **c / [<s²>]**

Linear relation between wind speed and wave slope variance [<s²>] (Cox-Munk):

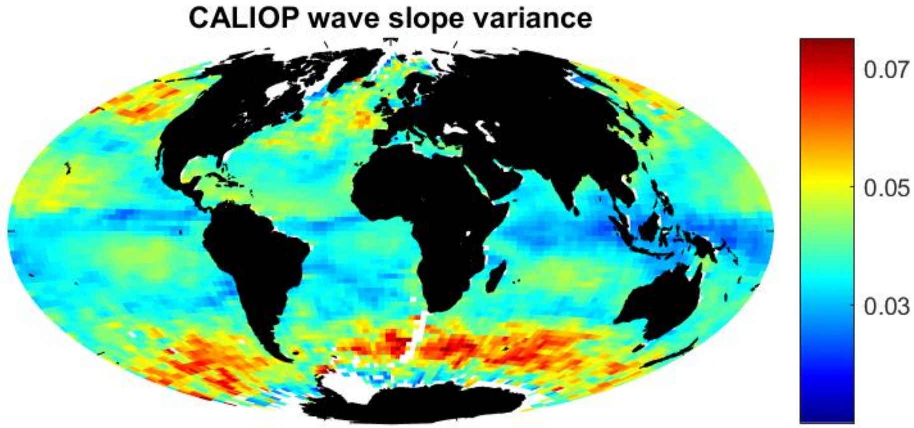
Lidar backscatter from ocean surface = **c / [<s²>] = c / (a+b*wind)**

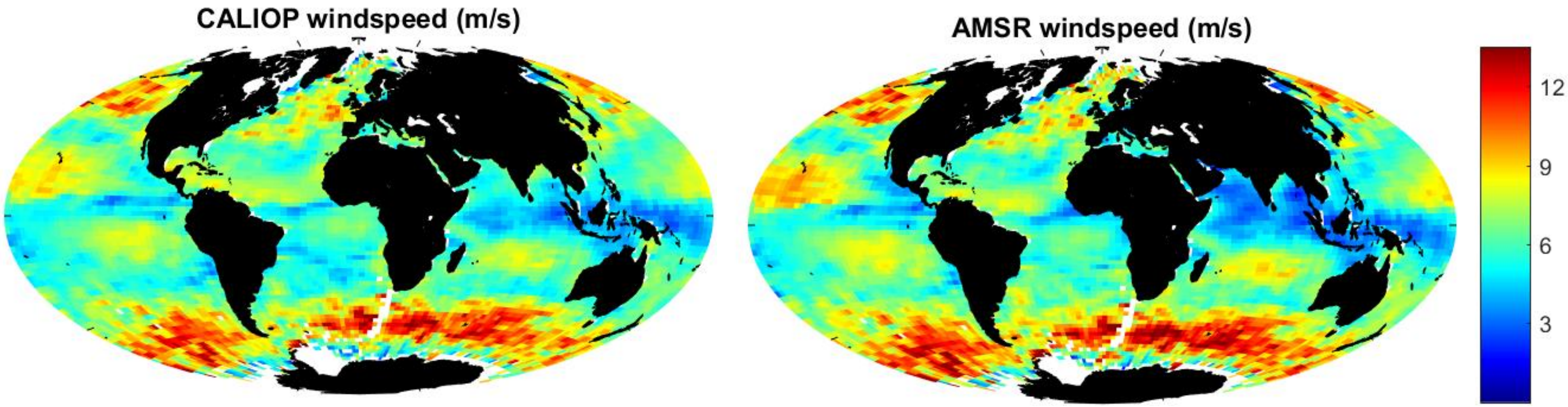


$$P(s)ds = \frac{c}{< s^2 >} e^{-\frac{s^2}{2<s^2>}} ds^2$$

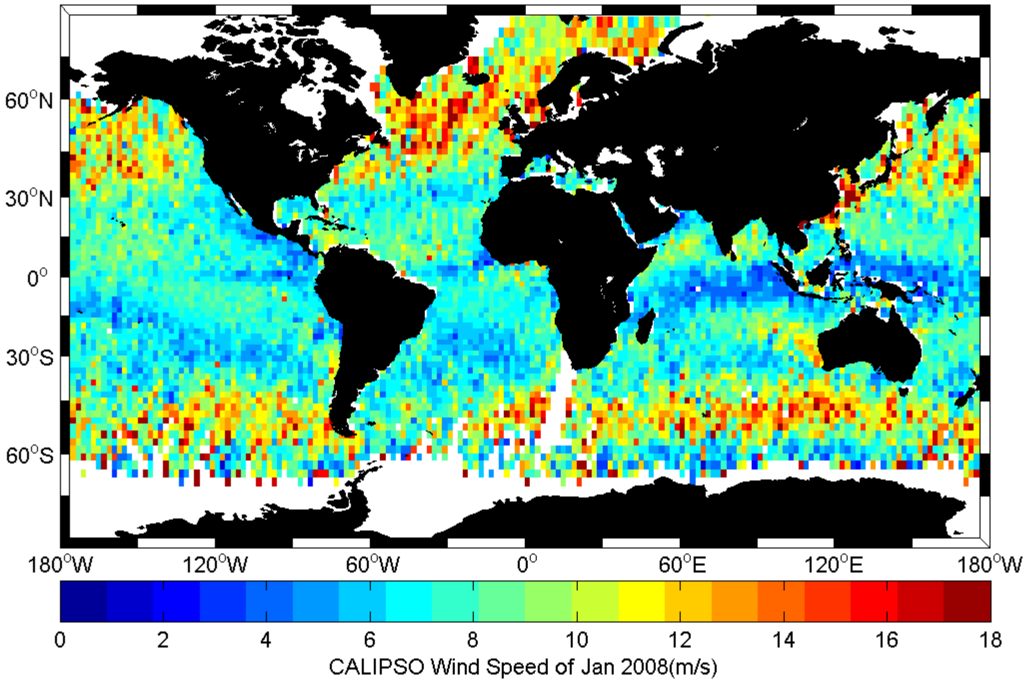
$$< s^2 > = a * Wind + b;$$

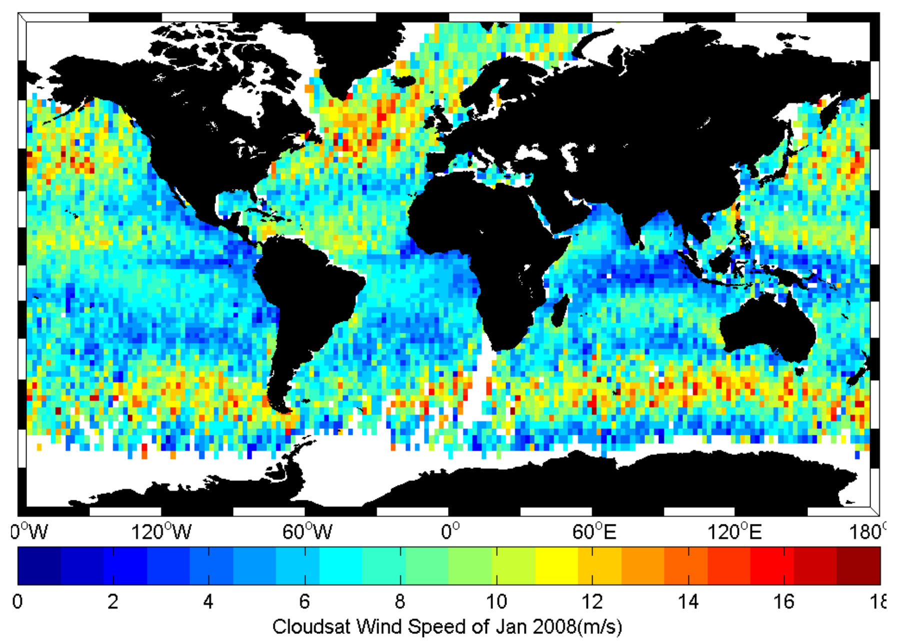
CALIPSO ocean surface wind speed vs AMSR-E



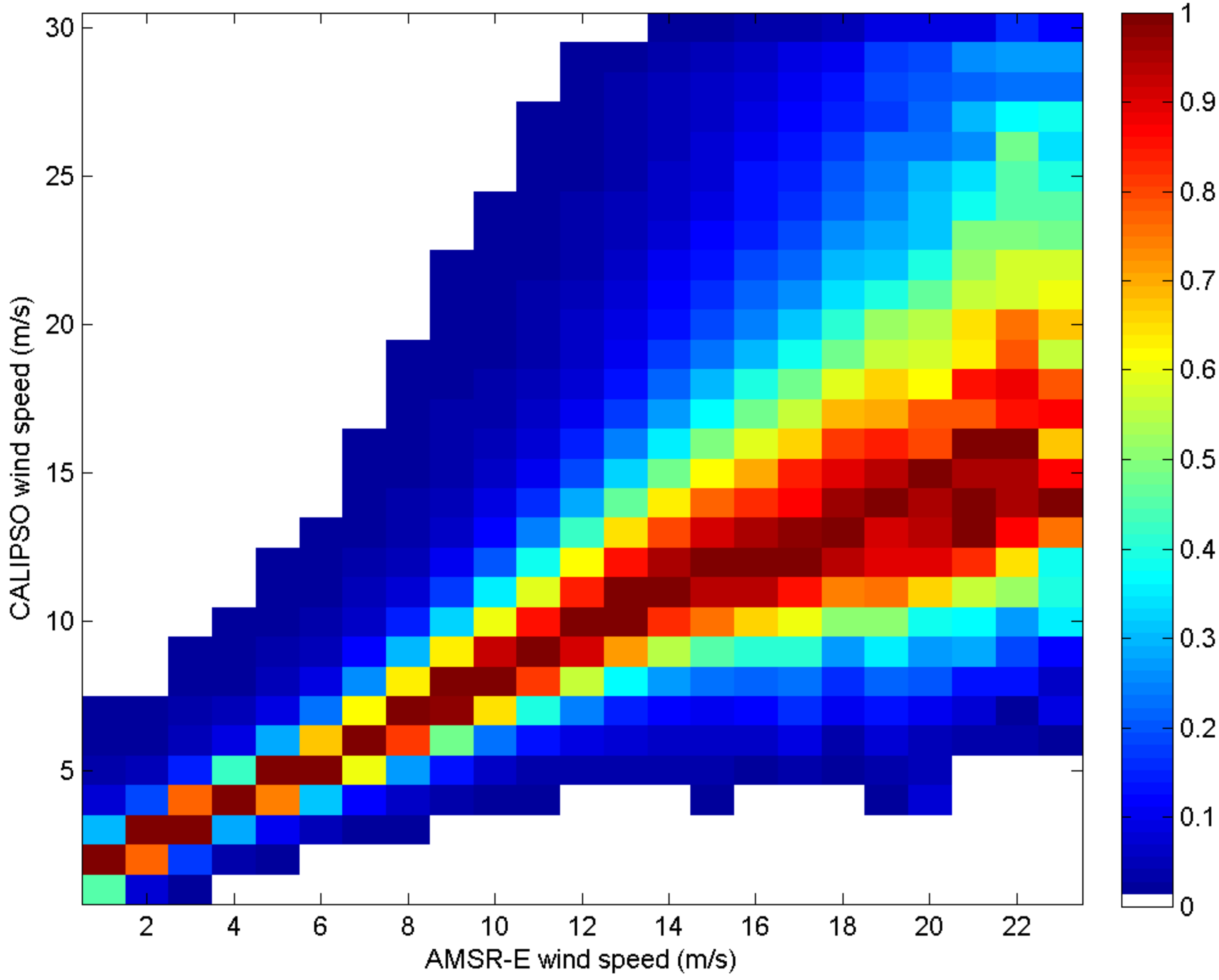


Monthly mean wind speed comparison: CALIPSO vs Cloudsat:





CALIPSO (wind speed measurement at 90 m footprint) captures wind gust and wind speed distributions within AMSR-E footprint

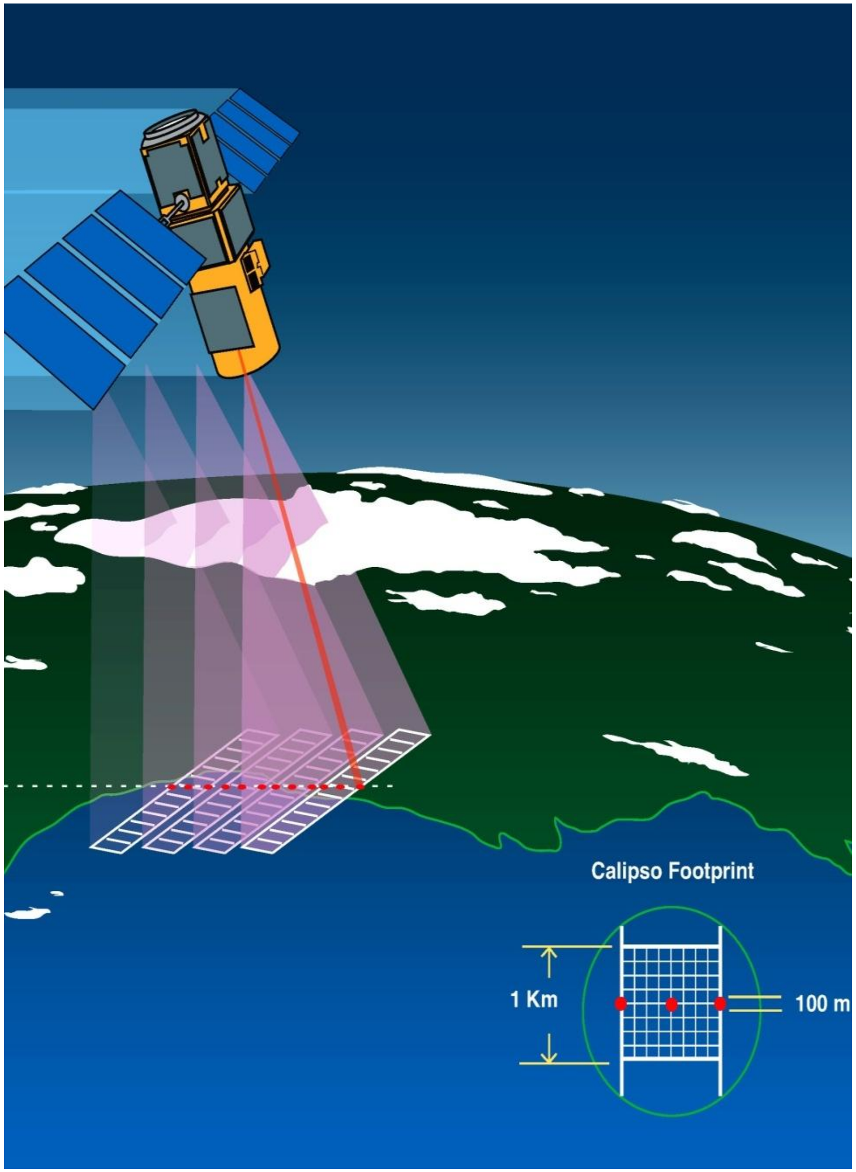


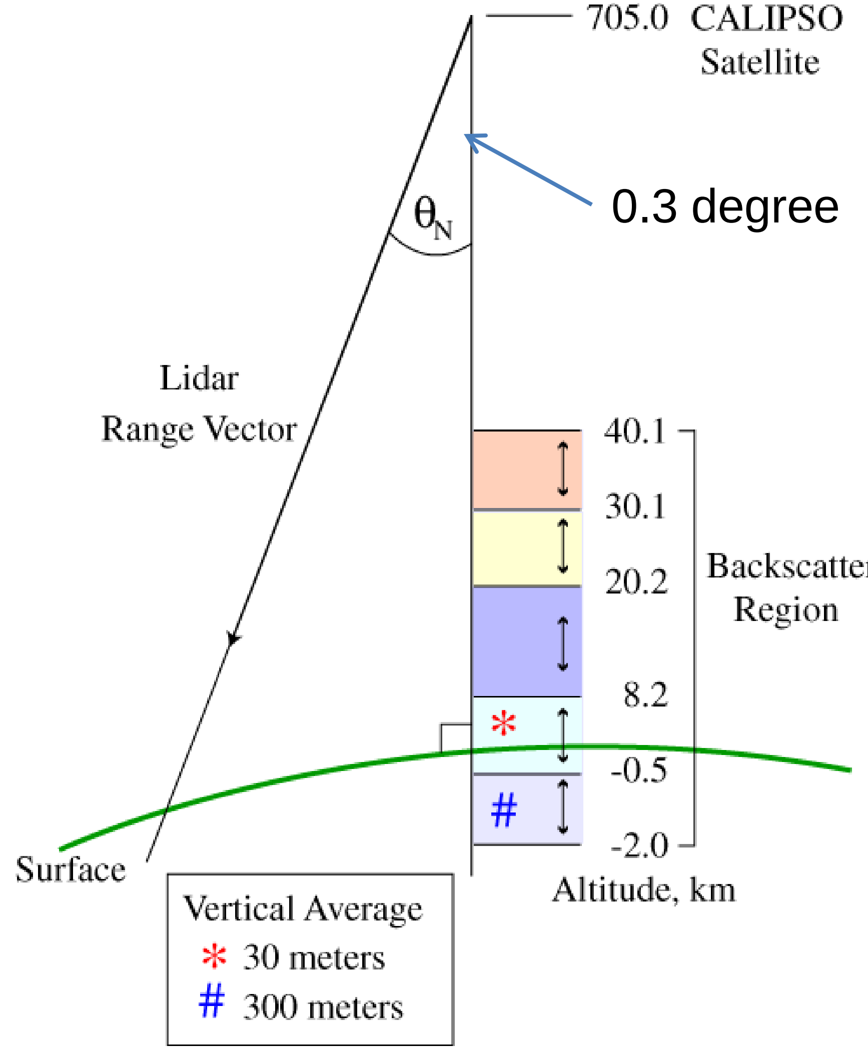
CALIPSO measures backscatter from particulates in the ocean

visible light penetrates well in water

Behrenfeld et. al., 2017: Space-based lidar shines new light on phytoplankton, **Nature Geoscience**, Volume: 10,; Pages: 118–122;

Altitude Region and CALIOP ocean subsurface range bins





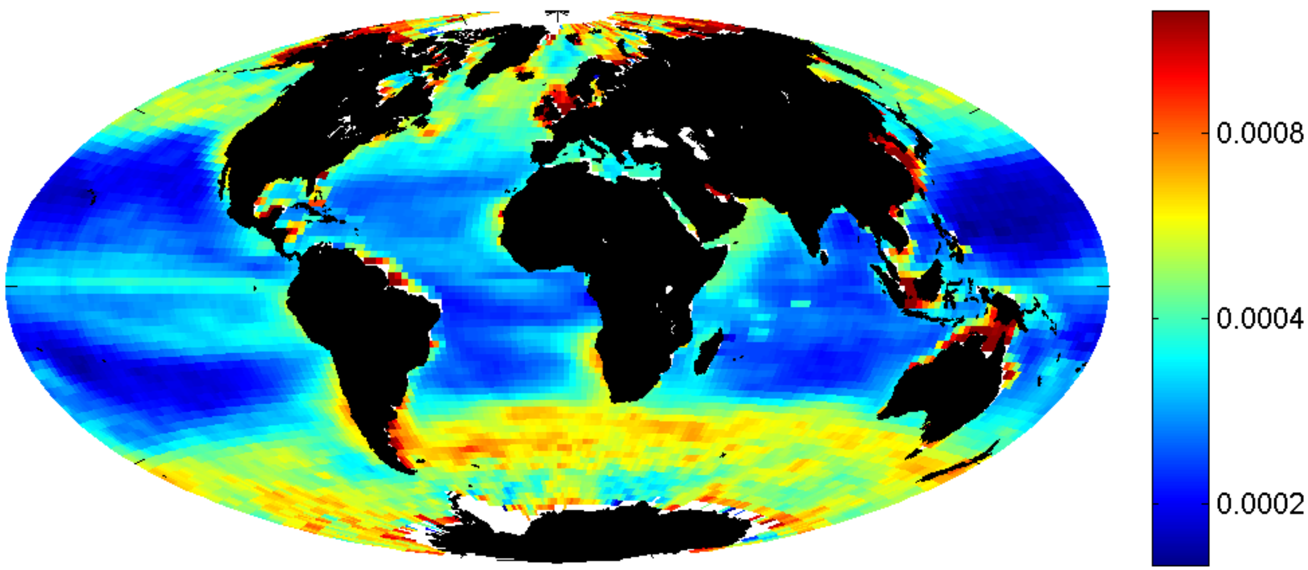
532nm Perpendicular: Subsurface Particulate Backscatter from 532nm Cross Polarization Signal

- For a linearly polarized incident lidar beam (e.g., CALIOP), spherical particles, Rayleigh scattering, and reflection at the ocean surface do not contribute significantly to cross polarization

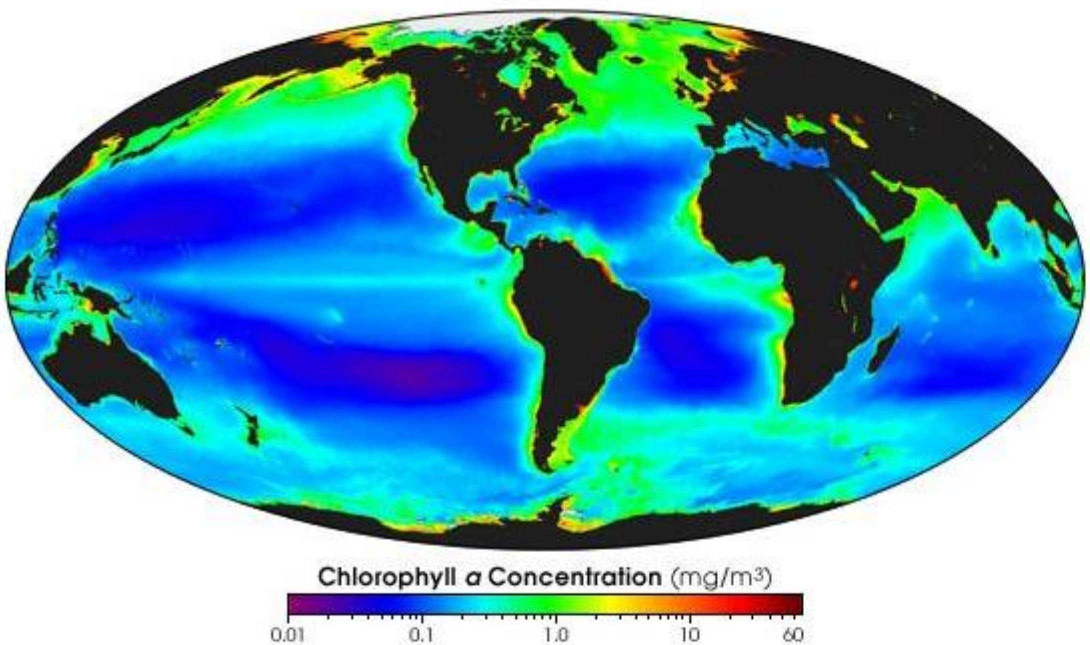
- Cross polarization (measured by the perpendicular channel) is dominated by backscattering of **non-spherical particles**

e.g., plankton and other non-spherical particles in the water

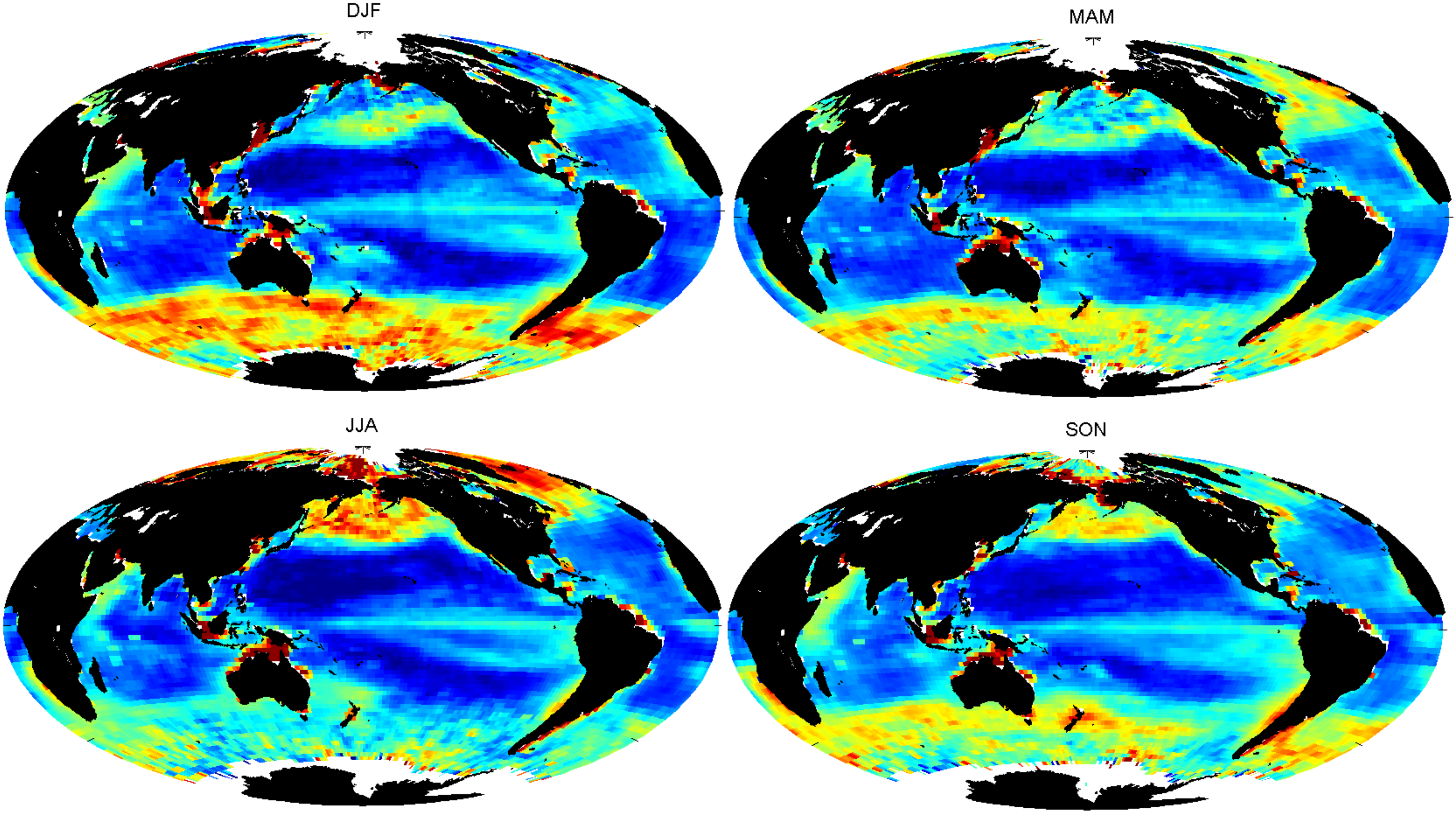
CALIPSO Cross Polarization Phytoplankton Backscatter (Sr^{-1})



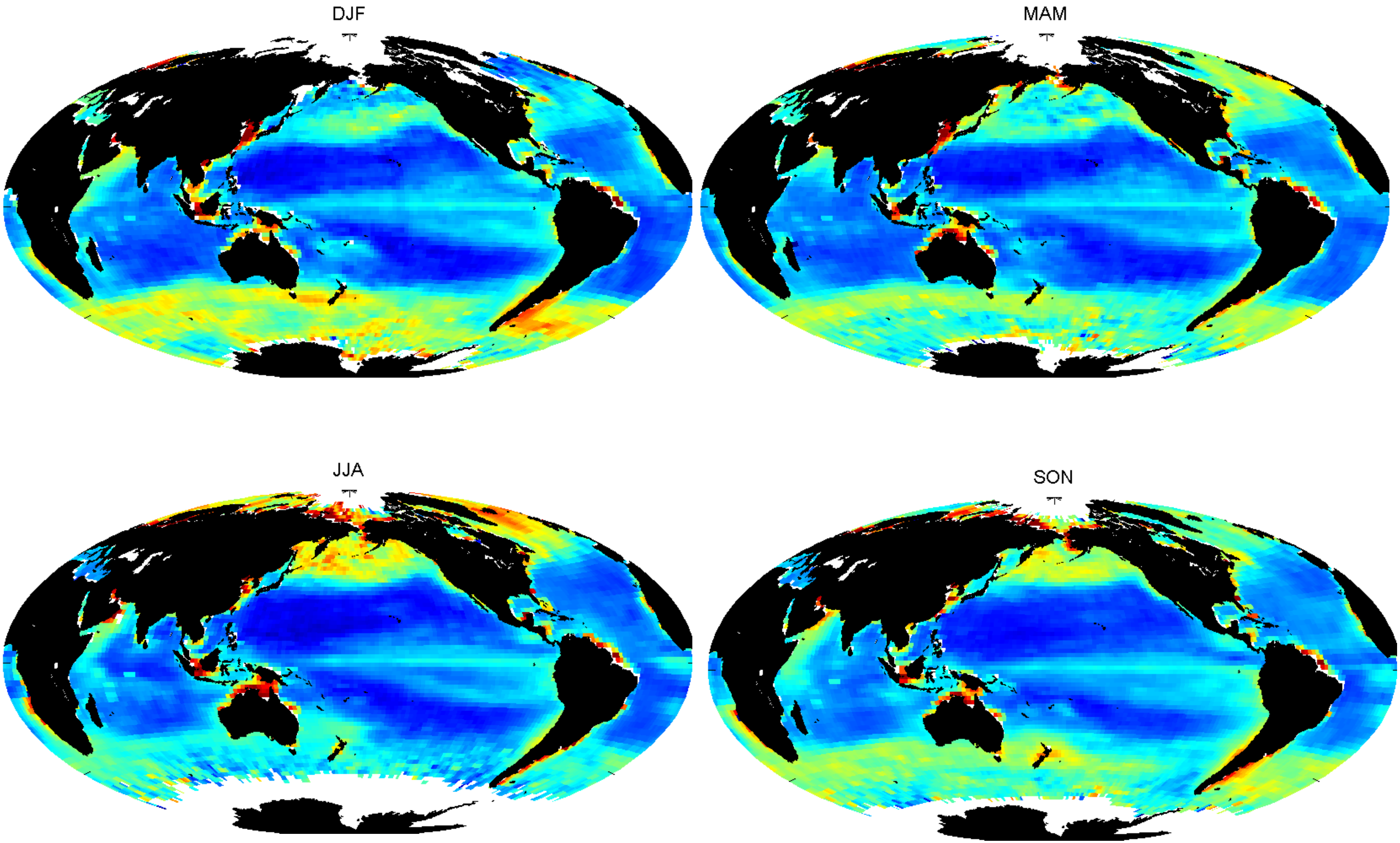
MODIS Chl-a Concentration



Seasonal Variations of CALIPSO Ocean Cross Polarization Measurements of Phytoplankton Backscatter

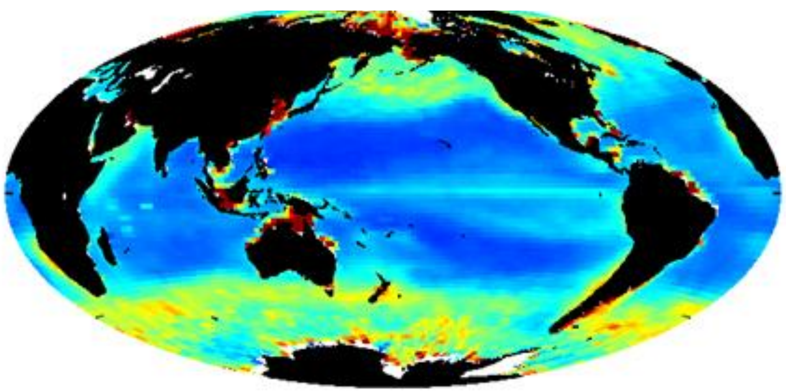


Seasonal Variations of CALIPSO BBP

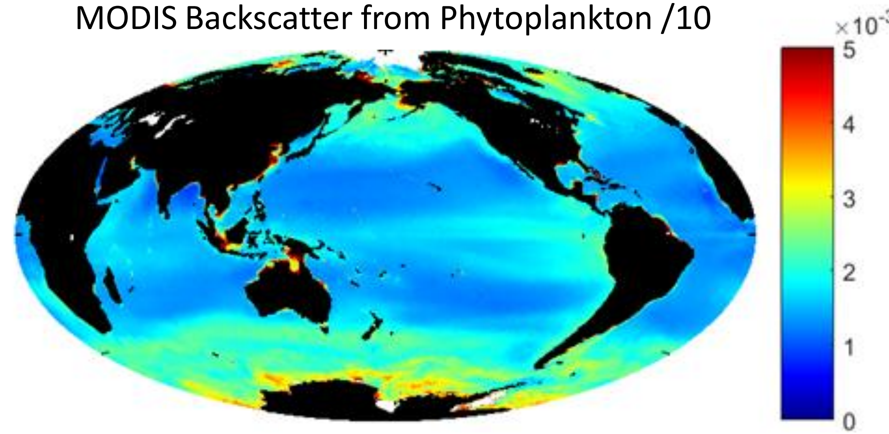


CALIPSO cross polarization measurements of phytoplankton backscatter: comparisons with MODIS

CALIPSO Cross polarized Backscatter

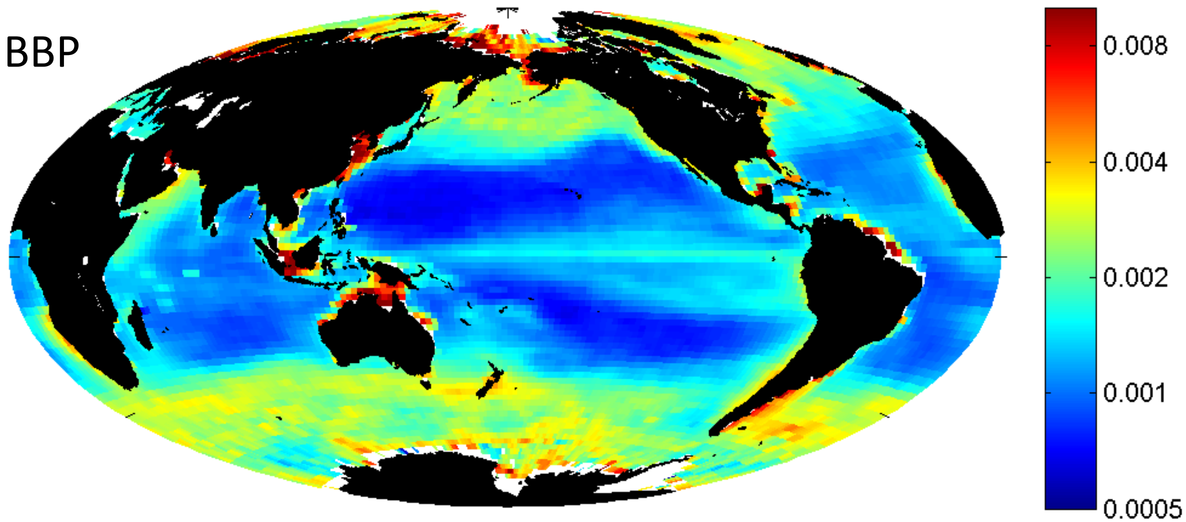


MODIS Backscatter from Phytoplankton /10

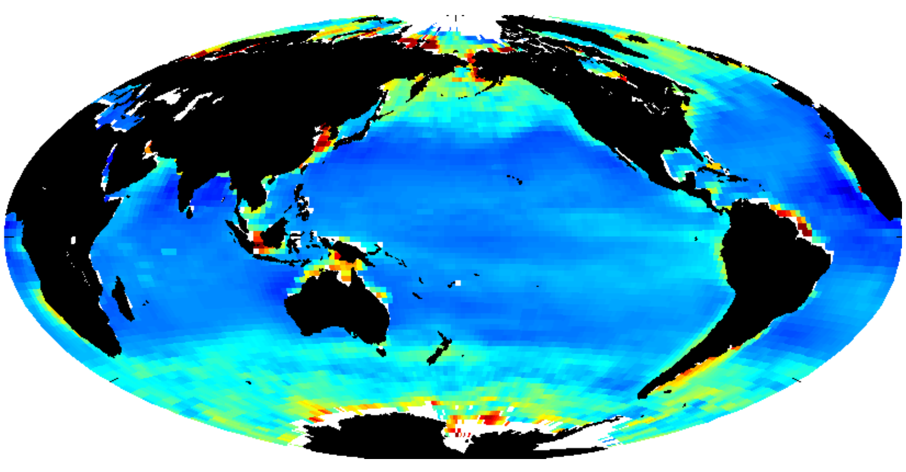


Phytoplankton particulate backscatter coefficient (1/m) estimate from CALIPSO, and comparisons with MODIS

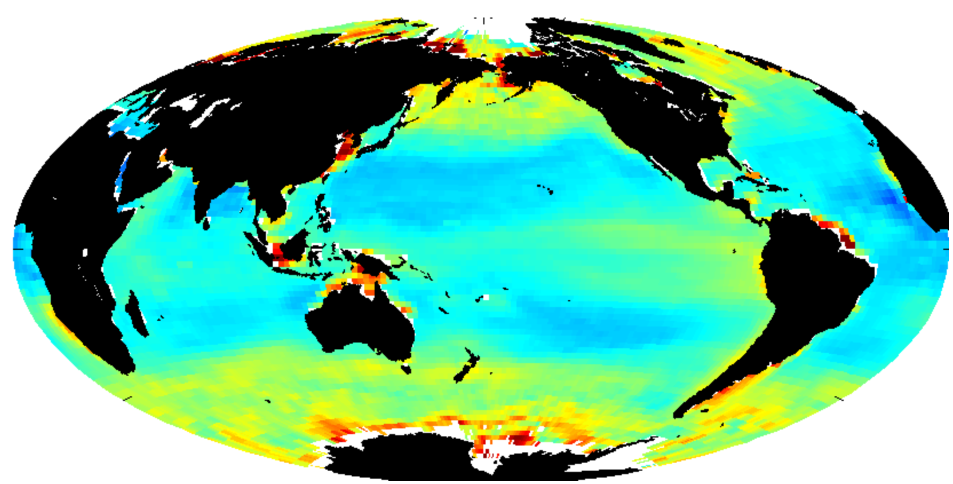
CALIPSO BBP



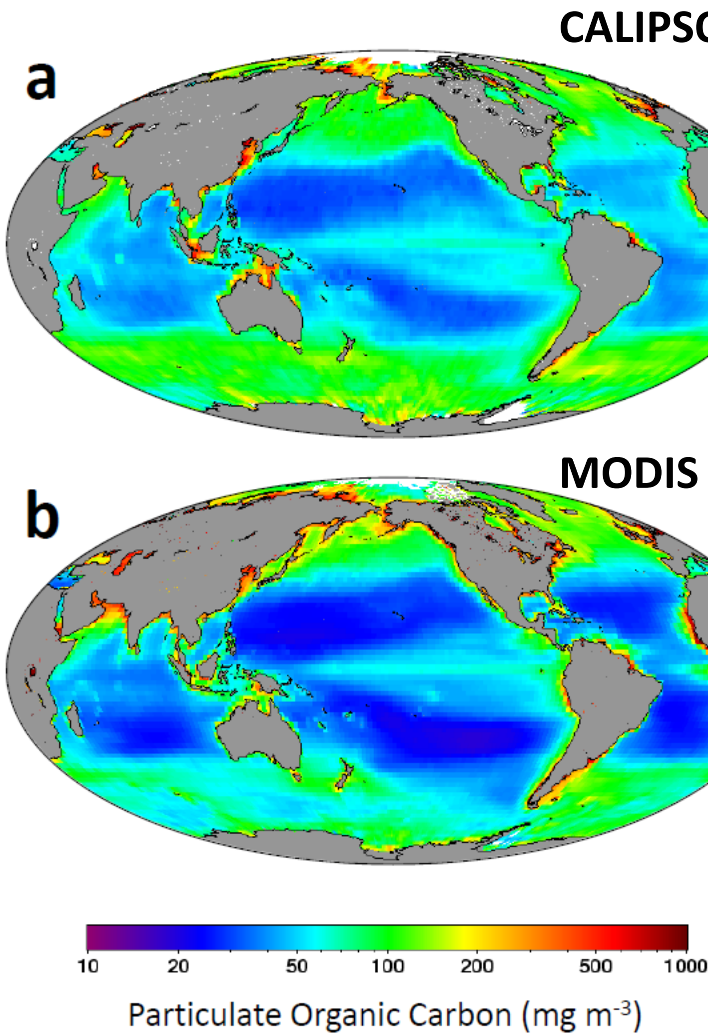
MODIS BBP: GSM Product



MODIS BBP: QAA Product



CALIPSO data used for estimating POC

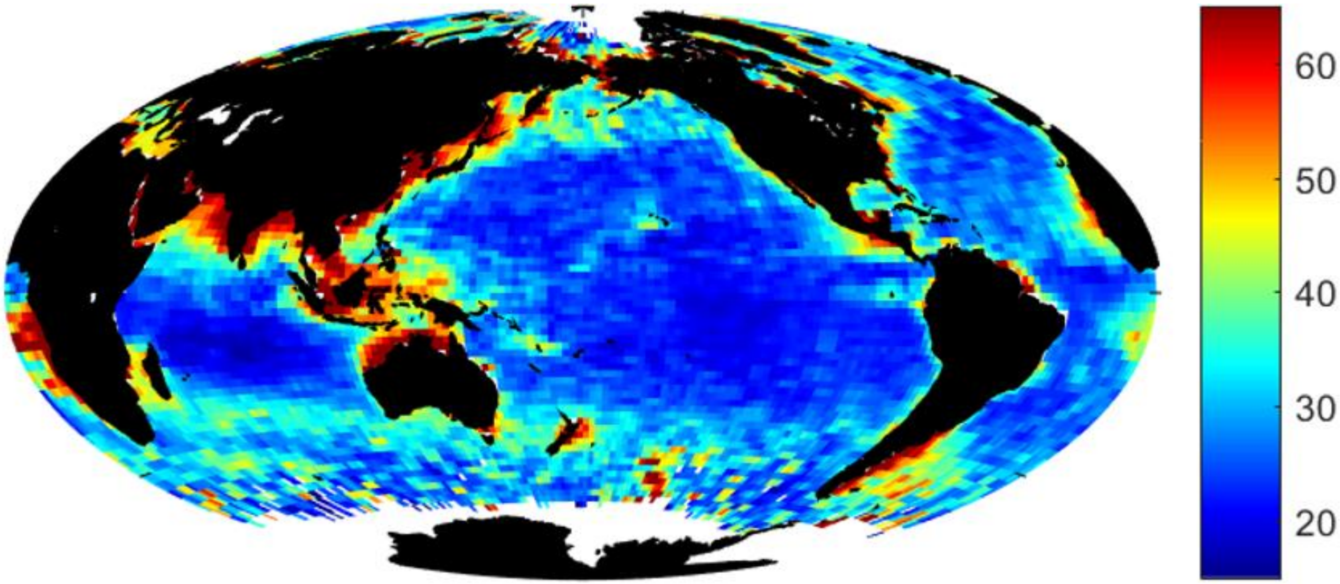


- Particulate Organic Carbon (POC) retrieved from CALIPSO spaceborne lidar compared favorably to the MODIS product
- CALIPSO retrievals use employ vertically-integrated subsurface data (i.e., not vertically resolved)

From: Behrenfeld et al., Space-based lidar measurements of global ocean carbon stocks, GRL, 2013

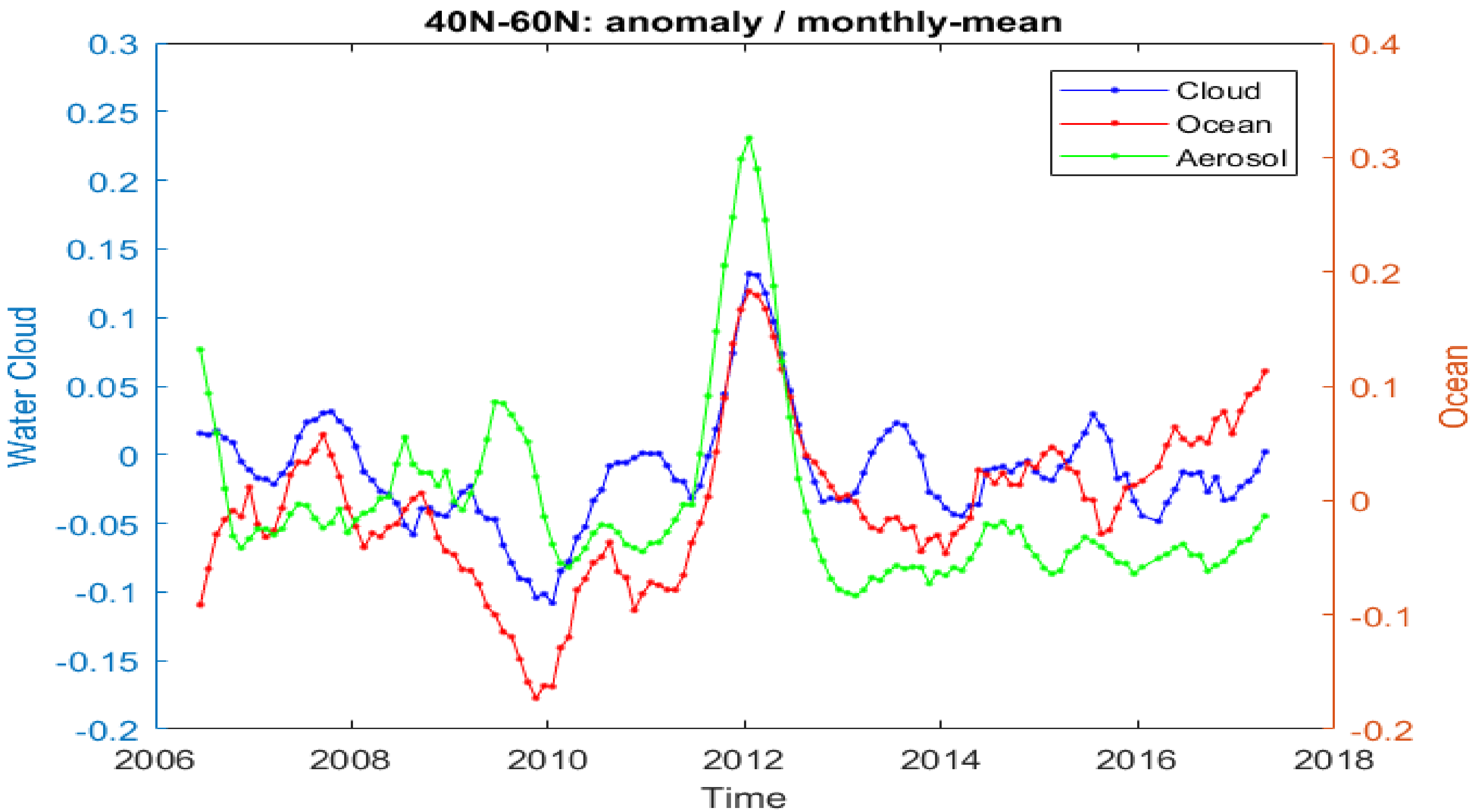
Data in each panel are climatological annual averages for the 2006 to 2012 period. Data are binned to 2° latitude by 2° longitude pixels.

Boundary layer aerosol lidar ratio (extinction / backscatter cross section, Oct 2016): highly correlated with phytoplankton



- *Aerosols with biological origin have larger lidar ratios*
- *Boundary laer aerosol lidar ratio is highly correlated with phytoplankton*

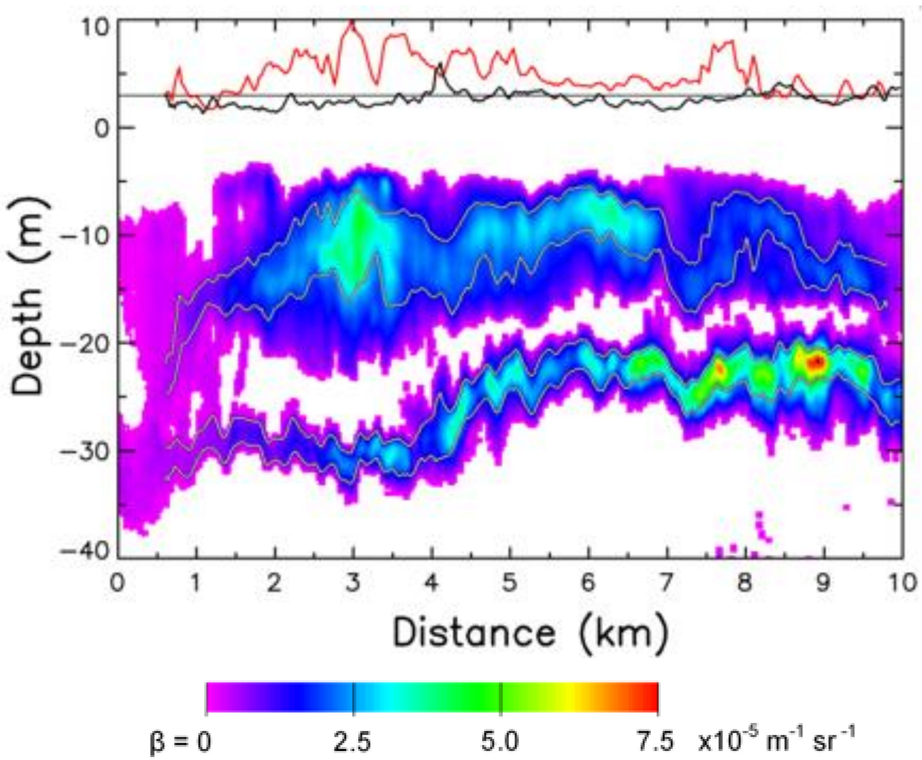
Temporal correlation of CALIPSO cross polarization backscatter by water clouds (blue), phytoplankton (red) and aerosol Sa (green)



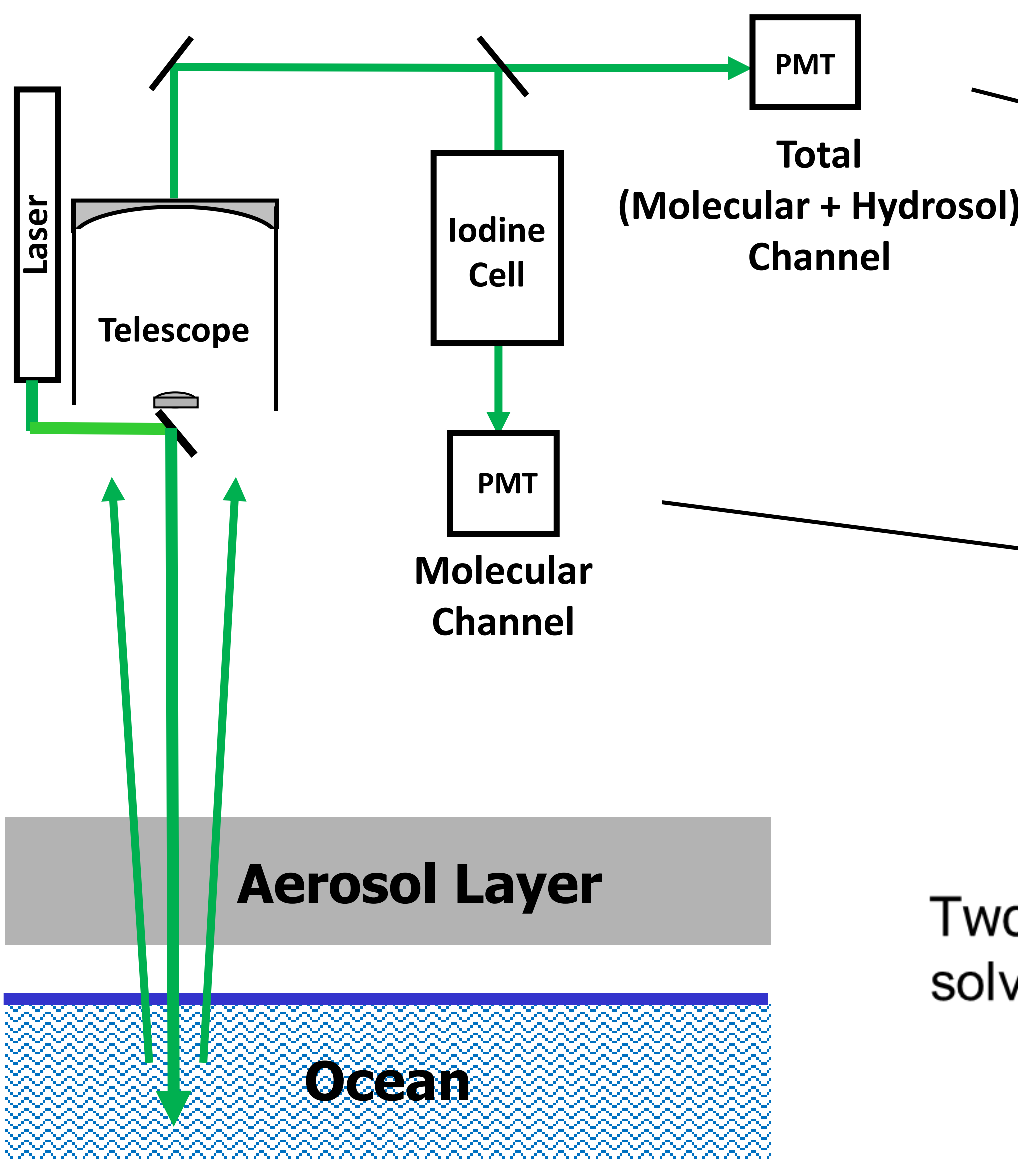
Future space lidar: going beyond CALIPSO with high vertical resolution

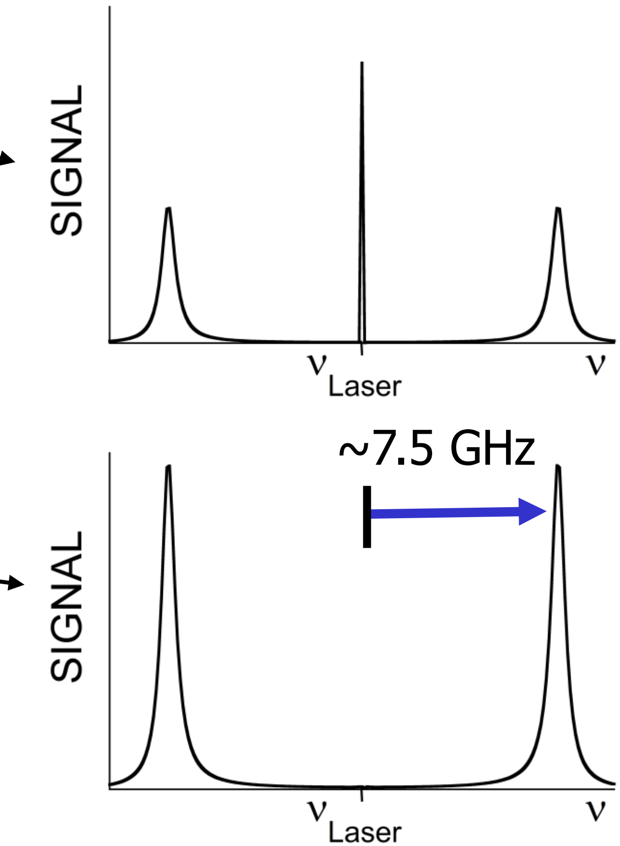
- CALIPSO sampling was 22.5 m in water and effective resolution was closer to XX m
- No technical obstacles to increasing lidar resolution
  - 1-m sampling
  - 2-3 m effective resolution
- Jim Churnside (NOAA) and others have demonstrated this from aircraft for decades. (Space lidar will not achieve this exceptionally high horizontal resolution.)

Airborne lidar data from NOAA FLOE lidar (Jim Churnside, NOAA)



Future space lidar: going beyond CALIPSO with high spectral resolution lidar (HSRL)





Two channels give two equations to solve for two unknowns:

- $\beta_p(\pi)$ (converts to b_{bp})
- Attenuation (~ K_d)

What do high spatial/spectral resolution lidars enable

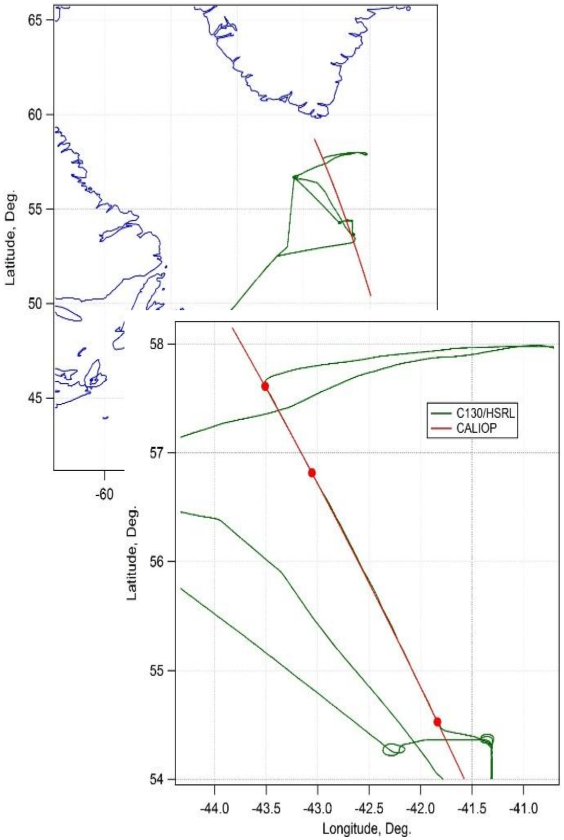
Atmospheric side:

- improved boundary layer height retrievals
- measurement of aerosol optical depth profile and improved typing of aerosols
- atmospheric wind speed

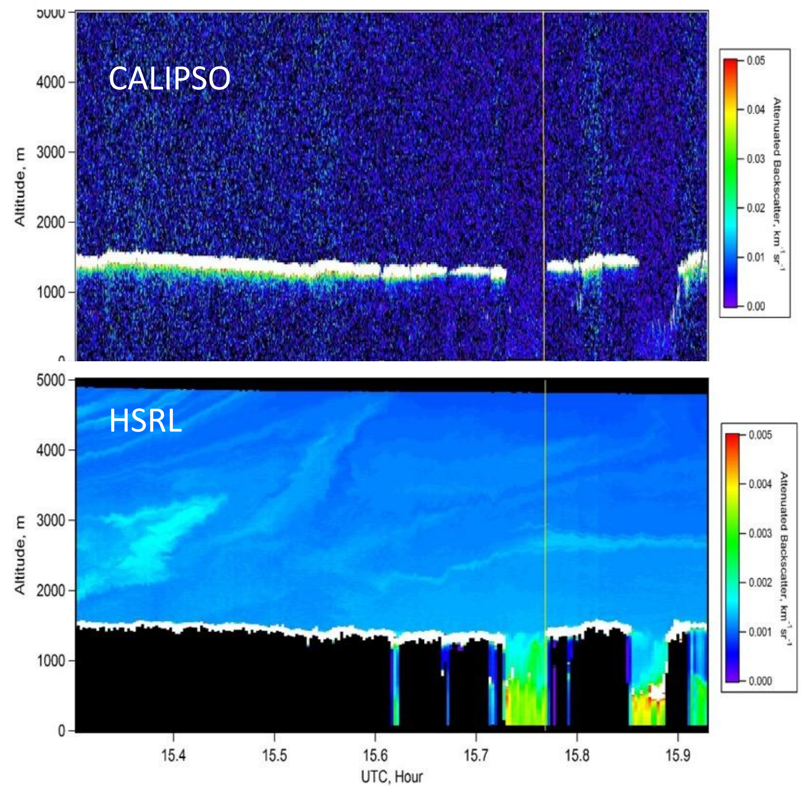
Ocean side:

- profiling of phytoplankton backscatter
- detecting bubbles
- potentially, detecting vertical changes of temperature/salinity

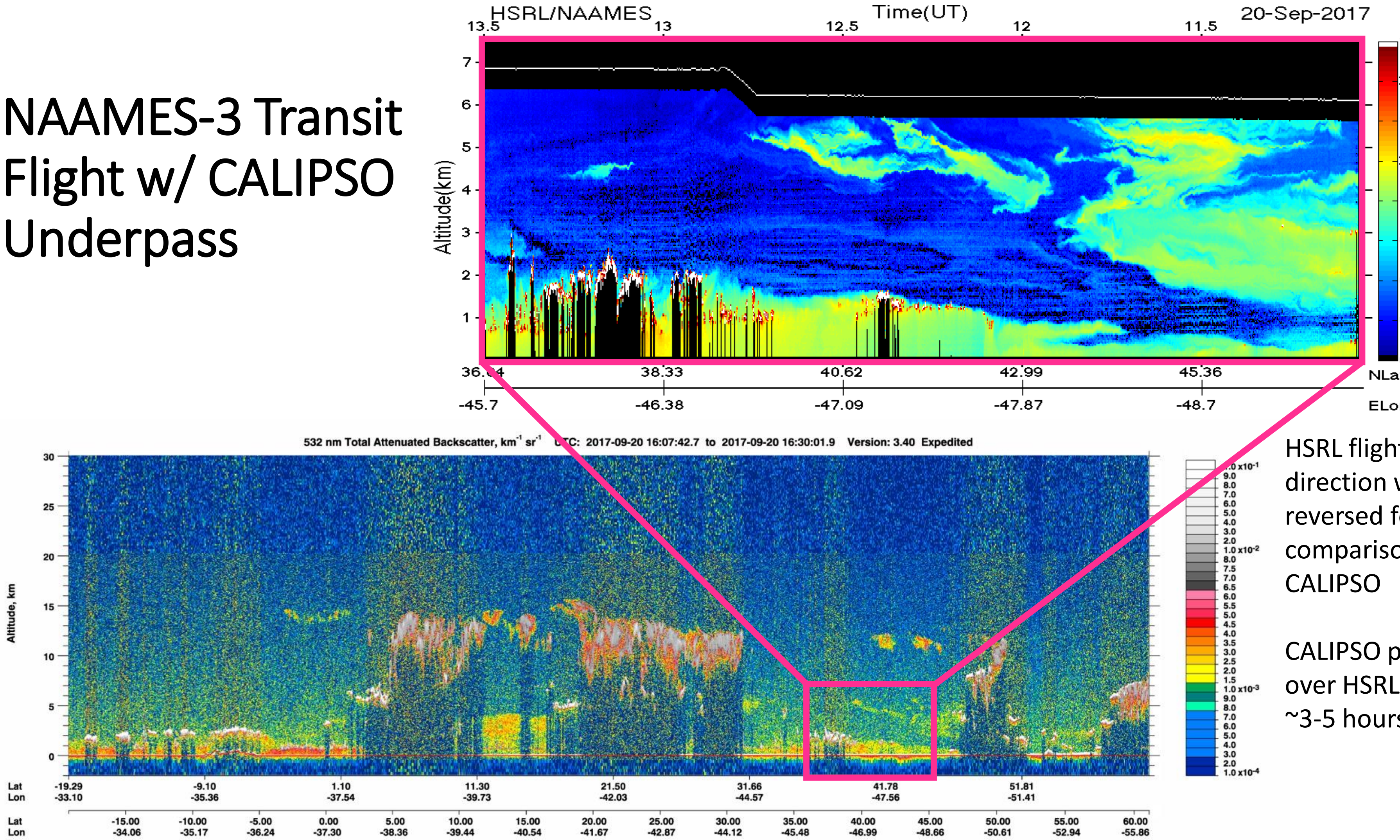
NAAMES-2 Science Flight w/ CALIPSO



Attenuated backscatter images



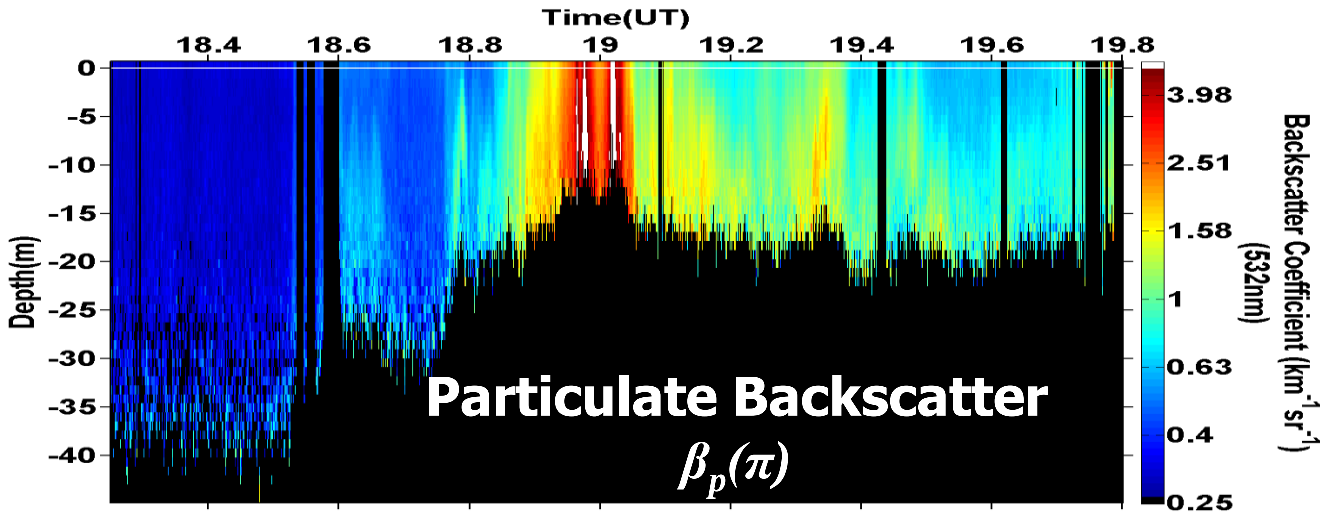
NAAMES-3 Transit Flight w/ CALIPSO Underpass

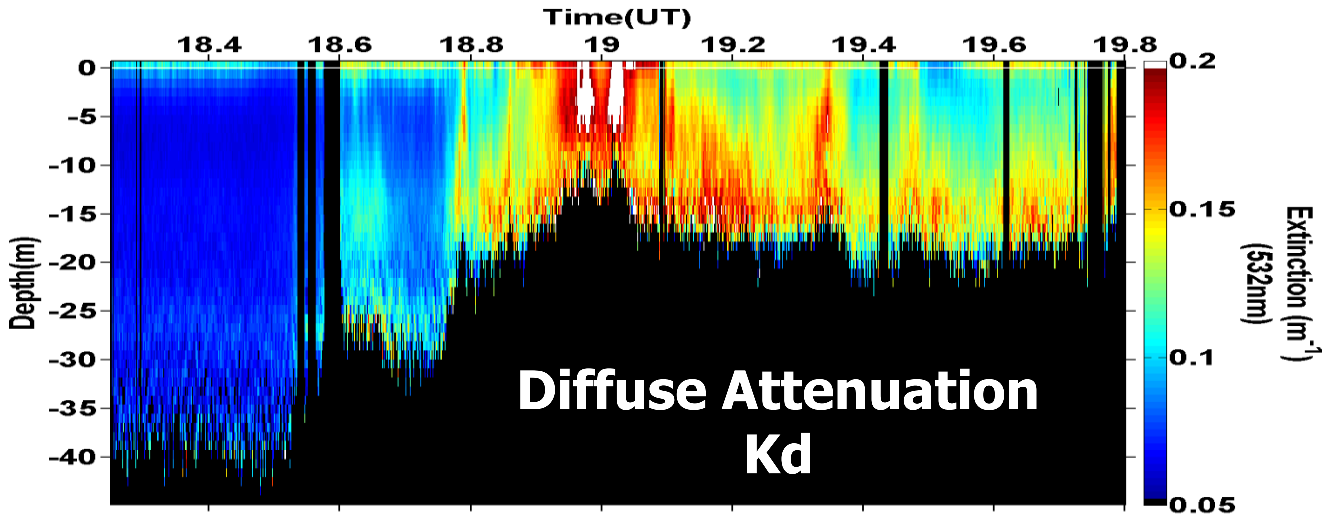


HSRL flight direction was reversed for comparison to CALIPSO

CALIPSO passed over HSRL track ~3-5 hours later

HSRL technique provides independent retrievals of particulate backscatter and attenuation



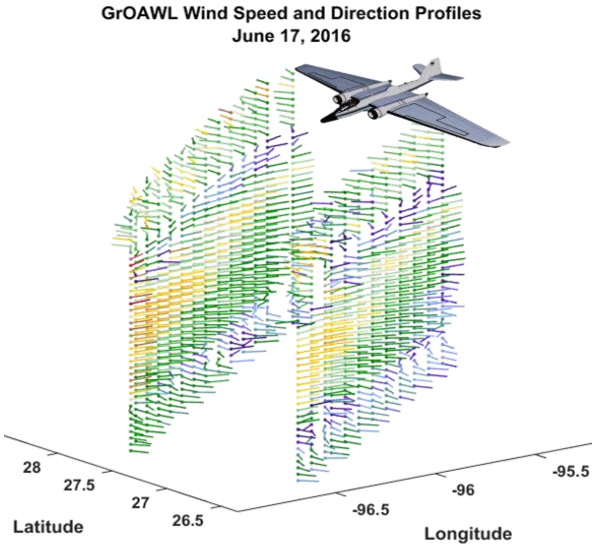


Lidar-Measured Global Wind Profiles (M. *Hardesty, S. Tucker*)

Recent Developments and Status

- **Aeolus**: Mission ready for launch August, 2018; *Completed: system design, airborne testing, prototype development, lifetime testing, space qualification.*
- **US Aerosol-only (coherent) winds mission:** 30-year ground and airborne development; *Completed: airborne laser transmitter development, airborne demonstrations.*
- **US Aerosol/molecular (direct):** Earth Venture ISS space-based aerosol-backscatter winds mission designed, costed, proposed; *Completed: Instrument prototype development; airborne testing and validation; mission implementation and science plans, proposal submitted.*

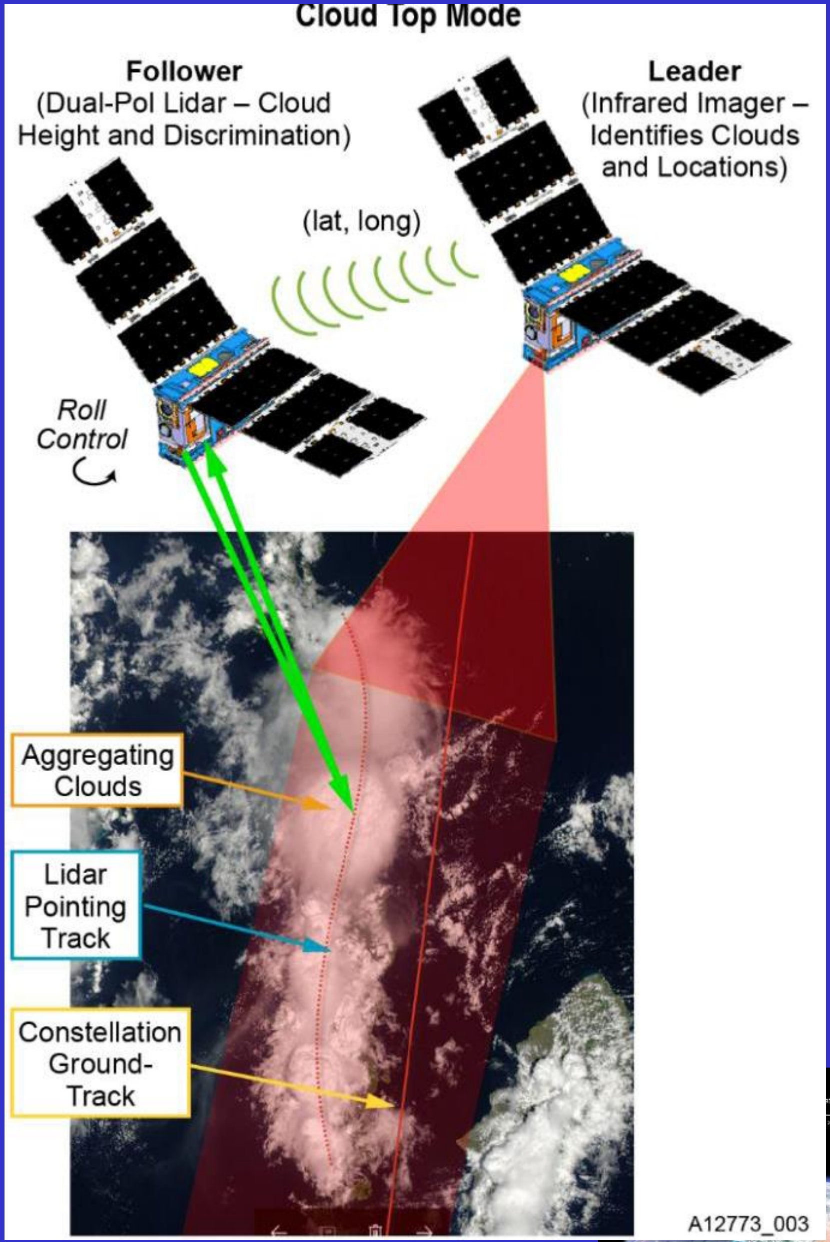
NASA/ESA Airborne Lidar

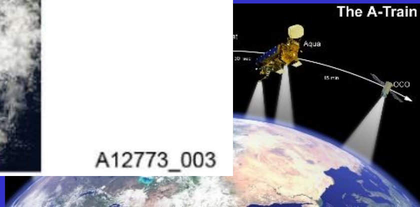


Innovative concepts for lidars on smallsat/cubesat

Cubesate Lidar for measuring convective aggregation

- The aa-Train utilizes two 6U CubeSats flying in formation.
- The Leader carries an infrared imaging instrument that identifies clouds in the scene and communicates their location to a Follower carrying a cloud top/water phase lidar.
- The Leader spacecraft calculates an optimal path and sends pointing commands to maneuver the Follower spacecraft to point the lidar to measure cloud heights.
- When combined, the volume of aggregating tropical clouds will be measured.



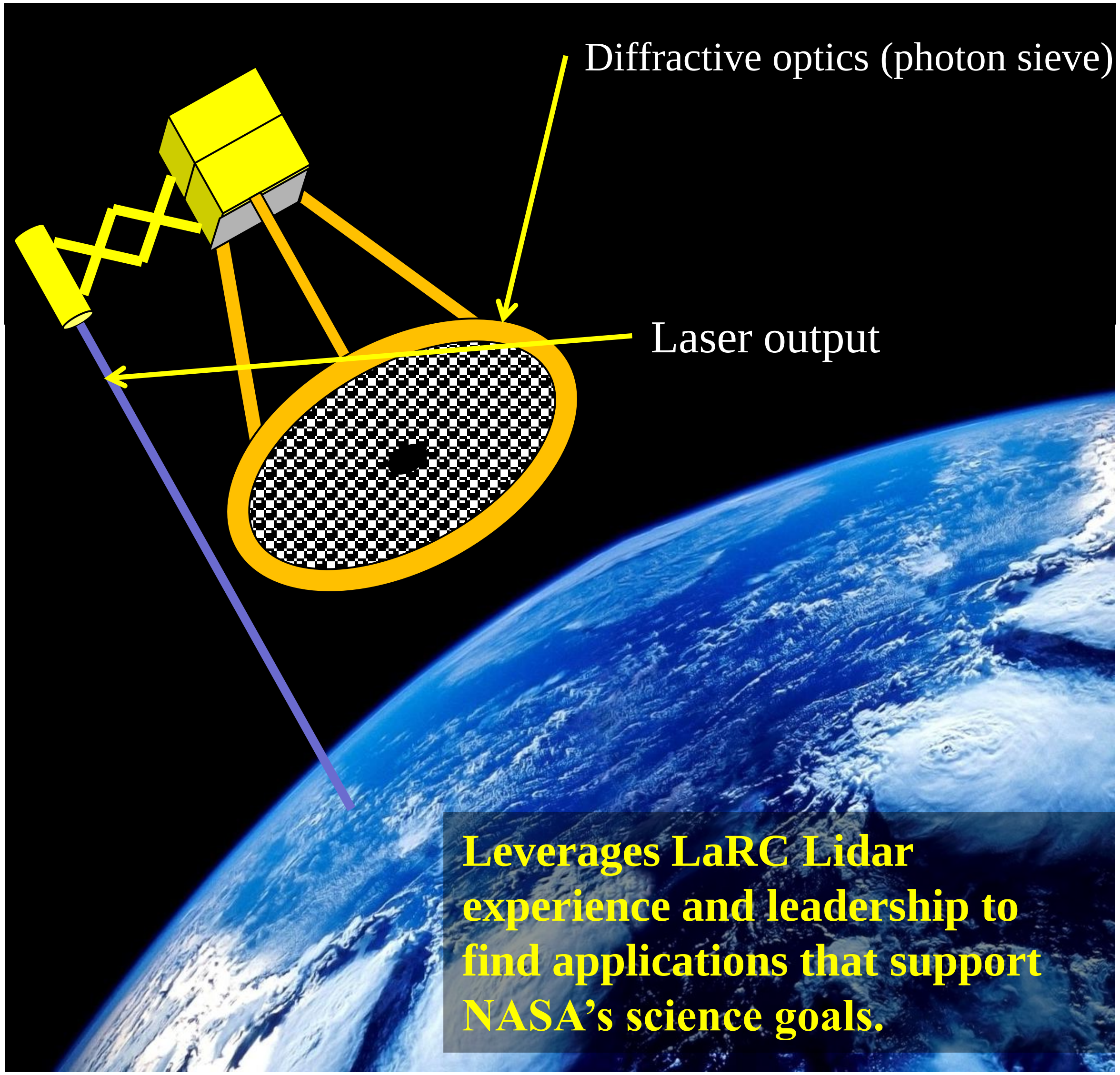


Photon Sieve for future LIDAR systems

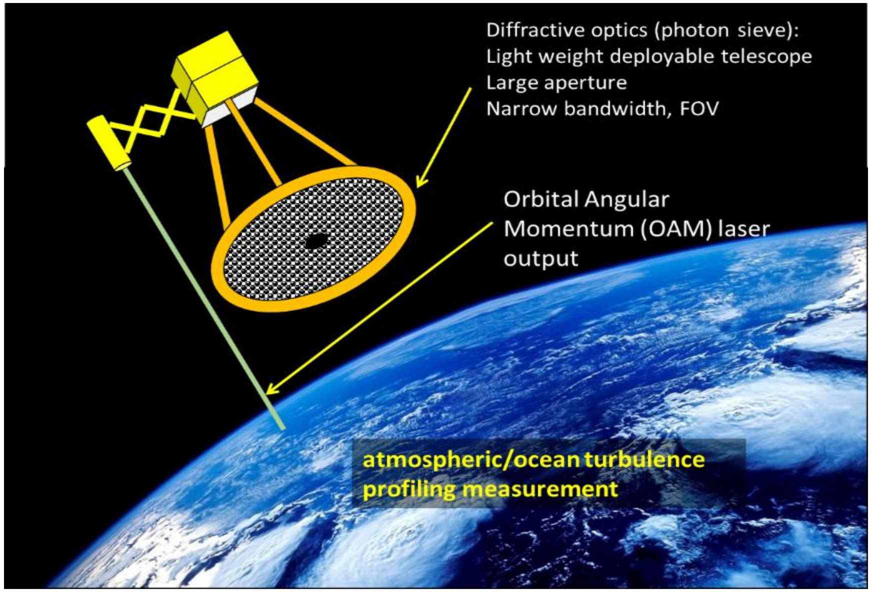
Model, Manufacture, characterize of light weight, deployable telescope concepts with the photon sieve diffractive optics.

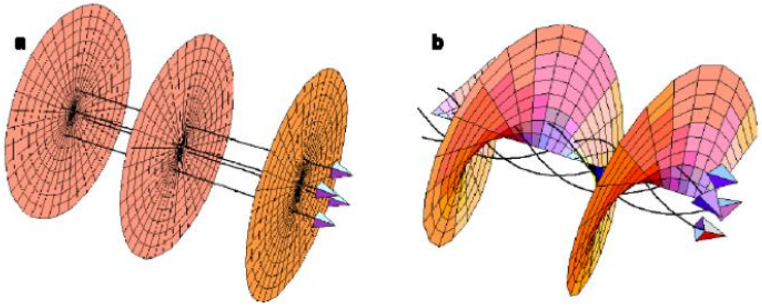
Study investigations:

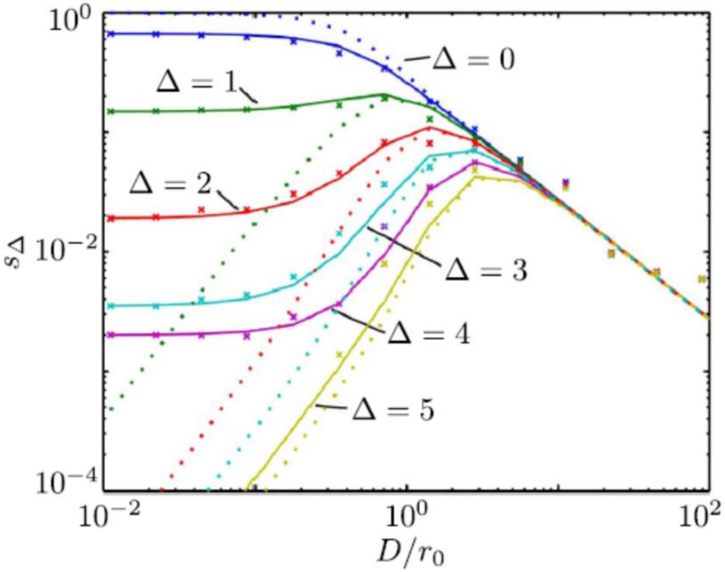
- Feasibility of Sieve
  - Optic Performance
  - Polarization maintenance
  - Noise filtering techniques
  - Detector schemes
- Mass/Volume/Cost
  - Find benefit thresholds



Turbulence measurements using laser beams with orbital angular momentum







Relationship between orbital angular momentum of light and coherent length, which is a function of turbulence structure parameter ($<C_n^2>$).

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- High Spectral Resolution Lidar and Potential lidar measurements for the decadal survey mission

- Lidar for cubesate under-development
  1. aa-train measurements of cloud 3D structure
  2. ONR ocean lidar for turbulence profiling