An Overview of Lidar Remote Sensing, the NASA CALIPSO Satellite Mission, and Some Atmospheric Applications of Lidar Data

Millersville University Department of Earth Sciences Seminar Series

September 26th, 2019

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NASA Langley Research Center

THE SCIENCE DIRECTORATE

Outline

- My career path
- Overview of my NASA branch: Atmospheric Composition
- Crash course in lidar remote sensing
- Lidars at Langley (CALIPSO and HSRL)
- CALIPSO science applications (my research)

My career path

- Millersville years (2006-2010)
  - Got involved with a research project with a few friends
    - *"An investigation of severe convection in the Chesapeake Bay region"*
- DOE Science Undergraduate Laboratory Internship (SULI) program @ PNNL (Summer 2010)
  - Used CALIPSO observations to study cirrus clouds
- Masters degree program @ UND (2010-2012)
  - Satellite remote sensing of aerosols and clouds (CALIPSO/MODIS)
- Doctoral degree program @ UND (2013-2018)
  - Emphasis on CALIPSO & air quality applications
- NASA Pathways program (summers of 2013-2015, 2017)
  - CERES group initially, then CALIPSO team
- Physical Scientist @ NASA Langley (2018-present)
  - CALIPSO mission (research, manuscript reviews, proposal writing)
  - A-CCP Science Impact Team member (aerosols, lidar simulations)

Northern Lights in North Dakota

(Pictures courtesy of Matt Eckhoff)

Atmospheric Composition (Lidar Science) Branch

NASA Langley Science Directorate

Langley Science Capabilities

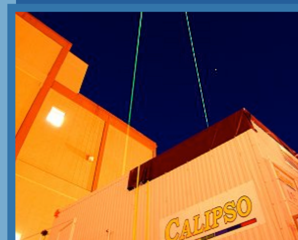
LaRC Provides All of the Elements for an End-to-End Approach

Example: Production of CALIPSO Data

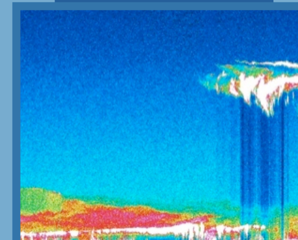
Mission Concept

Instrument system Development

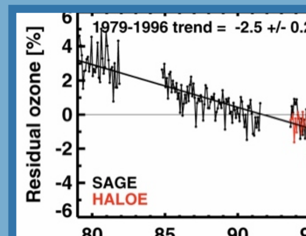
Calibration & Characterization



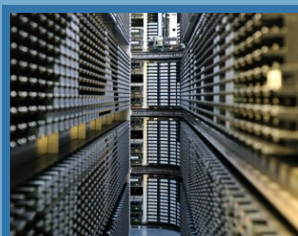
Retrieval Algorithms



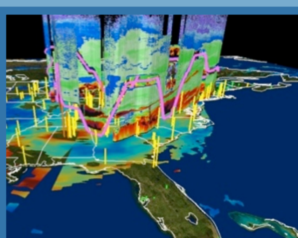
Data Validation via In-situ and HSRL instruments



Level 1, 2, and 3 Science Products



Data Distribution



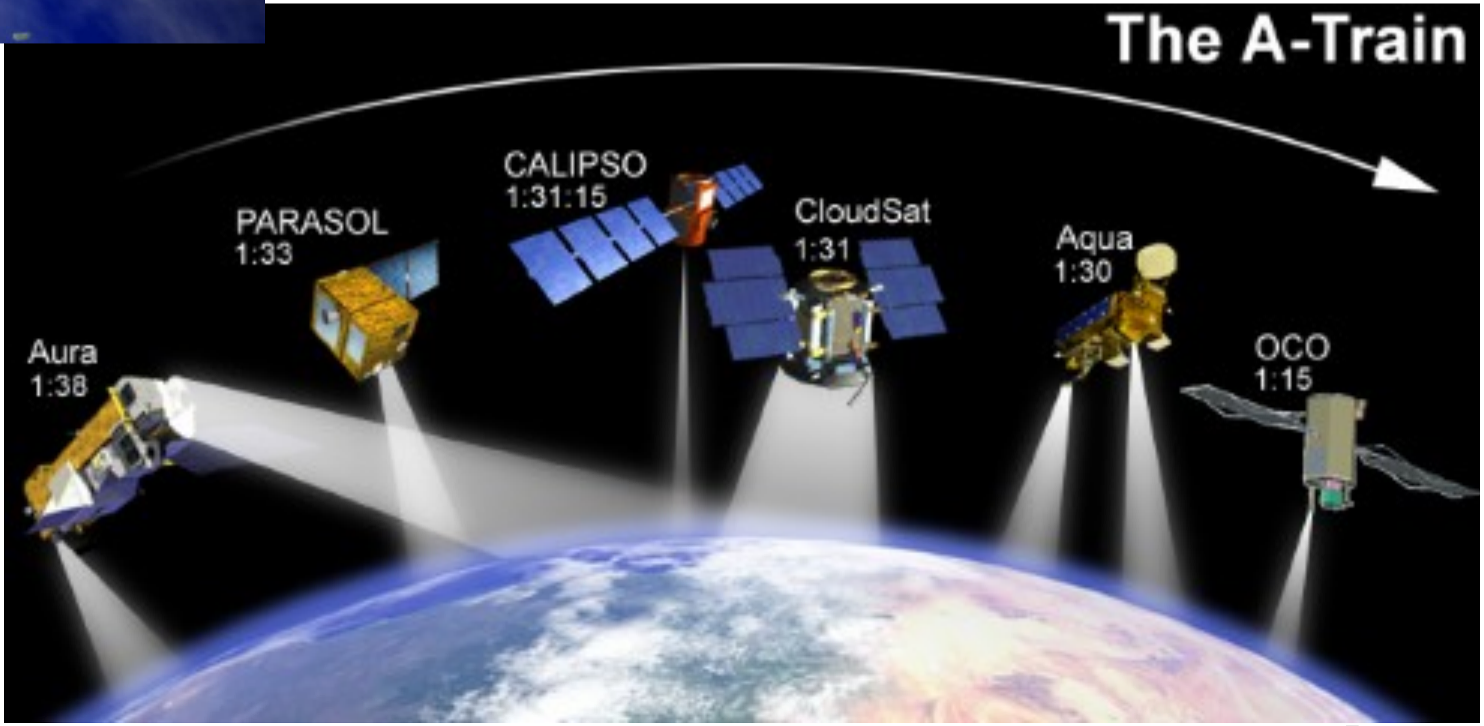
Applied Science For Societal Benefit and Education/Public Outreach

Long term, highly accurate records are essential for understanding our changing climate

CALIPSO and the A-Train

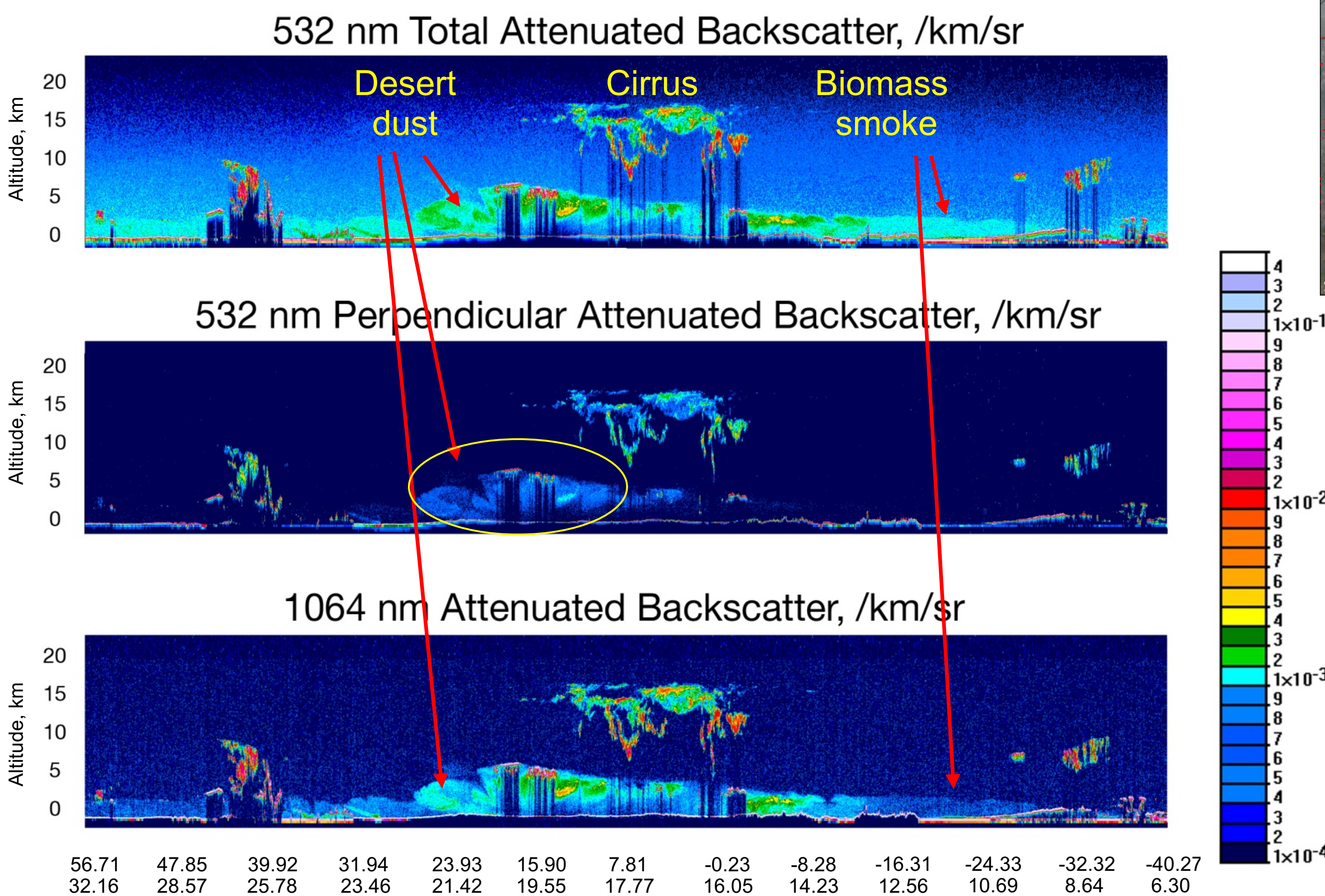
CALIPSO: **Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation**

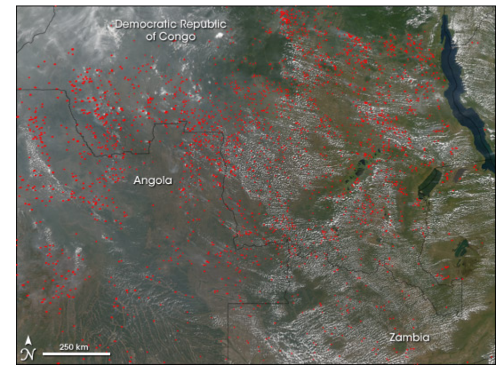
CALIPSO in its 14th Year in Space



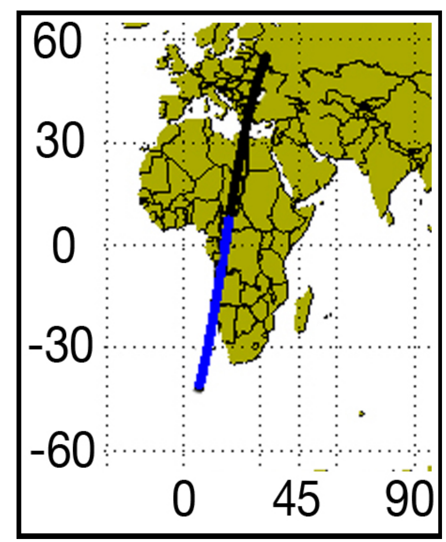
CALIPSO First-Light Observations

9 June 2006





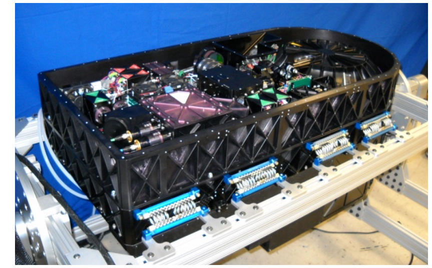
Fire locations in southern Africa from MODIS, 6/10/06



Langley Airborne Research Lidar Systems

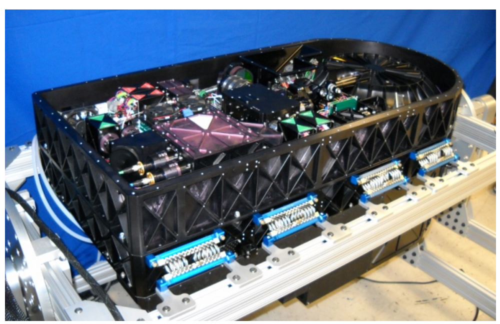
UV DIAL/HSRL
Ozone and aerosols
1983 - Present

LASE
Water vapor and aerosols
1994 - Present

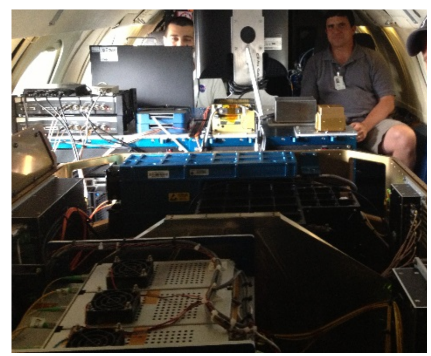


HALO
CH_4, H_2O, Aerosols, Clouds
2018

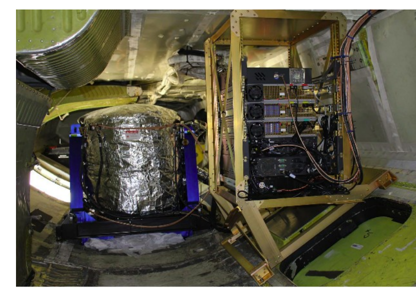
HSRL-1
Aerosols, clouds, oceans
2004 – Present



HSRL-2
Aerosols, Clouds, Ozone, Oceans
2012 - Present



ACES
CO_2
2014 - Present



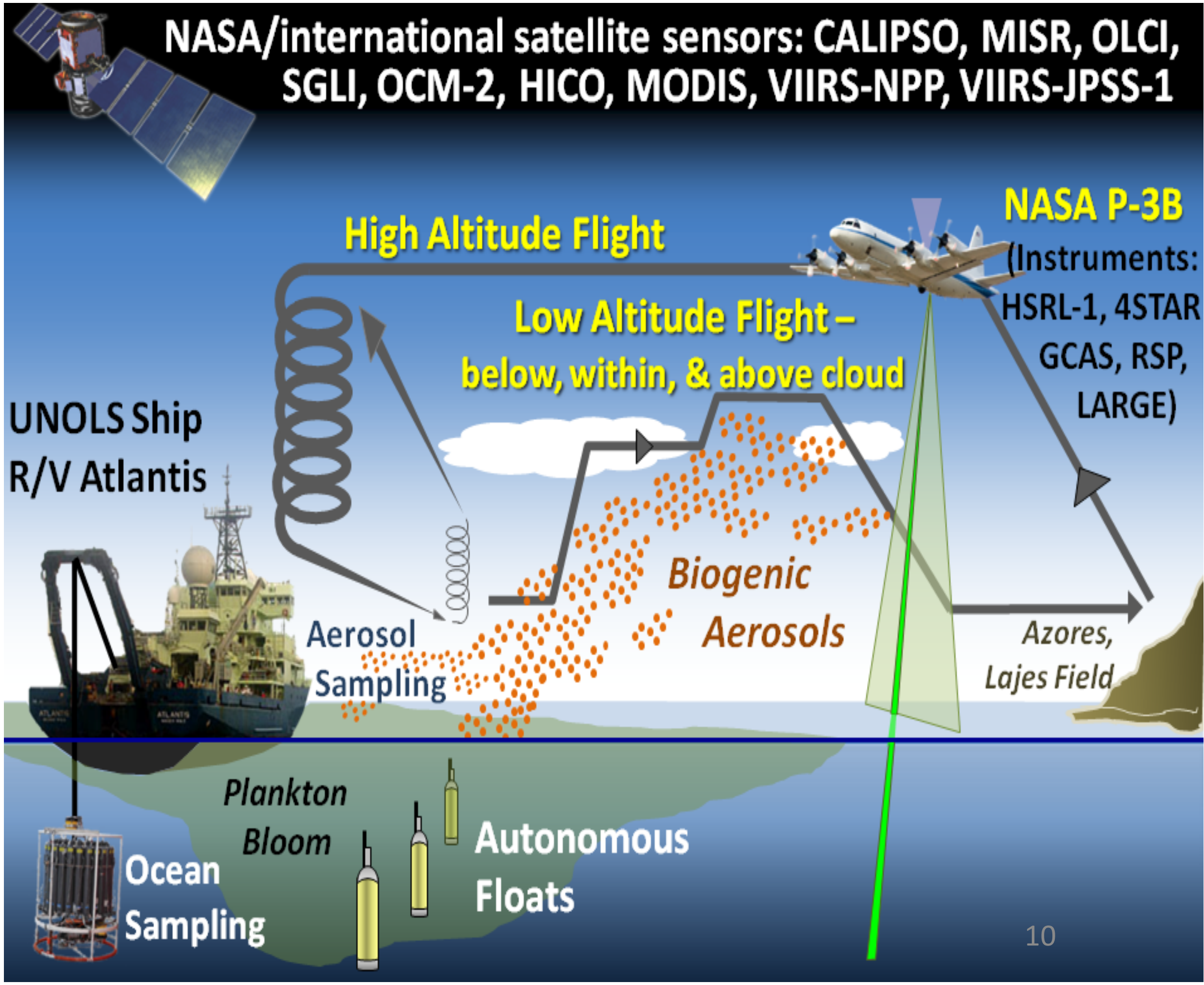
DAWN
Winds
2014 - Present

North Atlantic Aerosols and Marine Ecosystems Study (NAAMES)

5-year NASA Earth Venture Suborbital Project
PI: Mike Behrenfeld, Oregon St. Univ.
Mission management: NASA Langley

Objectives:
1. Define environmental and ecological controls on plankton communities
2. Define linkages between ocean ecosystem properties and biogenic aerosols

Four campaigns:
- Seasonally spaced
- 26-day ship deployments
- 19-day aircraft deployments
- 6 flights over ship per deployment



LIDAR: what it is and its importance in atmospheric science

- LIDAR stands for "light detection and ranging"
- Active remote sensor (i.e., sends out a pulse of laser light)
- Airborne, ground-based, and space-based instruments
- Allows for atmospheric profiling at high vertical/temporal resolution

- Atmospheric science applications:
  - Aerosols and clouds (e.g., climatic effects, air pollution, etc.)
  - Turbulent processes and diurnal cycle of PBL
  - Water vapor/ozone fluxes
  - Trace gases and stratospheric ozone depletion
  - Water droplets vs. ice crystals in clouds

A brief history of LIDAR

- 1930s: first attempts to measure air density using searchlight beams
- 1938: light pulses used to measure cloud base heights
- 1960: laser was invented
- 1963: first publications of atmospheric lidar observations
- Early 1970s: most basic lidar techniques demonstrated
- 1976: first textbook on lidar
- Since this time, lidar instruments have advanced with technology

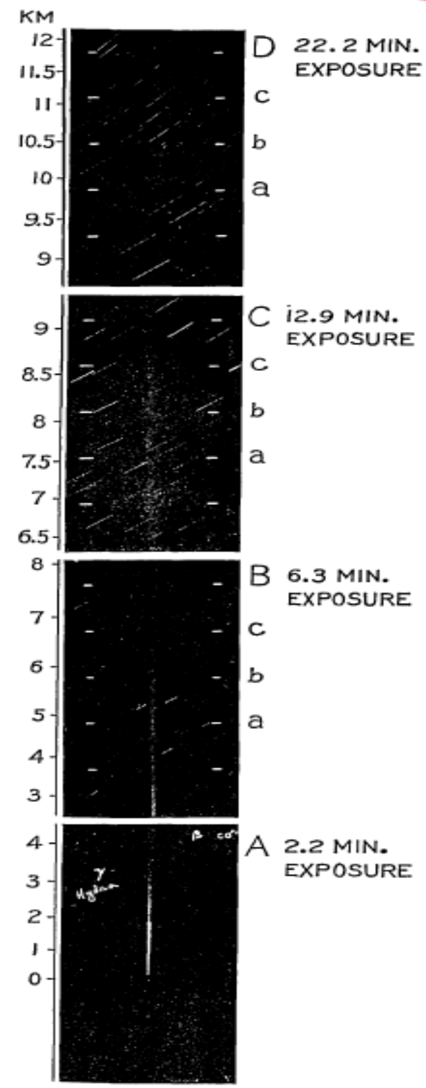


Fig. 1. Photographs of searchlight beam.

(Hulburt, 1937)

LIDAR setup

1. Light pulses from laser (transmitter)
2. Telescope collects photons backscattered (receiver)
3. Optical analyzer/detector selects specific wavelengths/polarization of collected light
4. Radiation directed onto detector, and optical signal converted into electrical signal
5. Sent to computer for data processing

Range distance and resolution

$$\boldsymbol{R = c(\frac{t}{2})}$$

$$\boldsymbol{\triangle R = c(\frac{\triangle t}{2})}$$

- R = range distance
- $\triangle R$ = range bin
- c = speed of light
- t = time
- Δt = resolution of time measurement (τ)

LIDAR equation

- The detected lidar signal can be written as:

  - $$\boldsymbol{P(R) = KG(R)\beta(R)T(R)}$$

- The power *P* received from a distance *R* is made up of four factors:

Determined by lidar setup:

  - *K* = summarizes performance of lidar system (ability to capture light)
  - *G(R)* = describes range-dependent measurement geometry (distance effects)

Measureable quantities:

  - *β(R)* = backscatter coefficient at distance *R*
    - Ability of atmosphere to scatter light back into direction from which it comes
  - *T(R)* = transmission term
    - Describes how much light gets lost on way from lidar to distance *R* and back

LIDAR equation

- The lidar equation in a more common form is:

- $P(R,\lambda) = P_0\left(\frac{c\tau}{2}\right)A_\eta\frac{O(R)}{R^2}\beta(R,\lambda)exp[-2\int_0^R \alpha(R,\lambda)\,dR]$

K term | **Geometry term** | **Backscatter term** | **Transmission term**

- Detected signal will also consist of a background contribution
  - Greater during daytime conditions

- Detector noise is another source of undesired signal

Types of lidar & techniques

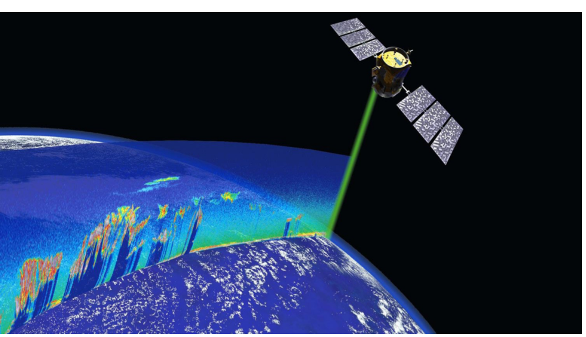
- Elastic backscatter, or Rayleigh-Mie lidar
  - Classic form of lidar…one laser emitting a single wavelength, with one detector measuring the radiation elastically backscattered from molecules/particles
  - Elastic scattering → process in which the wavelength of radiation remains unchanged
  - Example: CALIOP aboard the CALIPSO satellite
- High Spectral Resolution Lidar (HSRL)
- Micropulse Lidar (MPL)
- Differential absorption (DIAL; atmospheric gases)
- Raman (temperature profiles)
- Resonance (upper atmosphere applications)
- Doppler (winds)

(www.arm.gov)

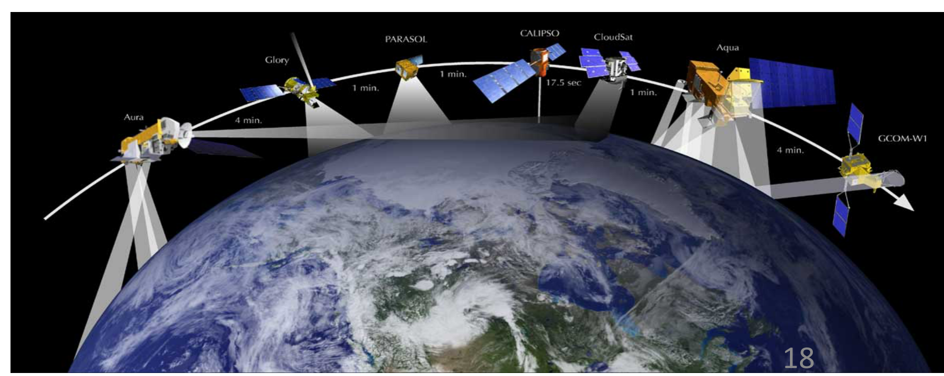
(www.arm.gov)

Lidars at Langley: CALIPSO satellite mission

- The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission
  - International collaboration between U.S. (NASA) and France (CNES)
  - Launched on April 28th, 2006
  - Vertical structure of aerosols & clouds in atmosphere
  - Flew in formation of A-Train satellite constellation (~705 km altitude)
  - Since September 2018, flies in the C-Train with CloudSat (~17 km below A-Train)



(www.nasa.gov)

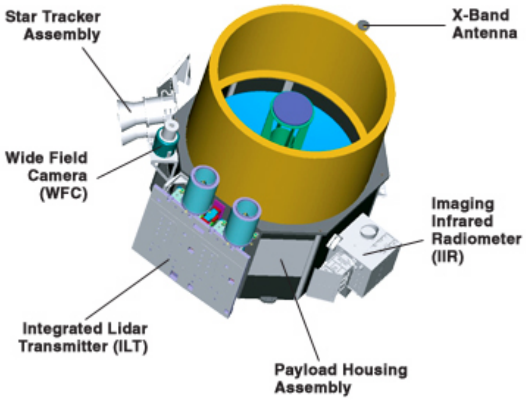


(https://science.nasa.gov/earth-science/a-train-satellite-constellation)

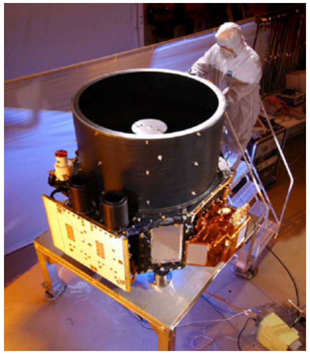
Lidars at Langley: CALIPSO satellite mission

CALIPSO payload

- Active
  - Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)
    - Two-wavelength (532 and 1064 nm) polarization-sensitive lidar providing high-resolution vertical profiles of aerosols and clouds
- Passive
  - Imaging Infrared Radiometer (IIR)
    - Three-channels used to obtain information on cirrus cloud particle size and infrared emissions activity
  - Wide-Field Camera (WFC)
    - Daytime images for cloud uniformity and broader meteorological view of area



(https://www-calipso.larc.nasa.gov)



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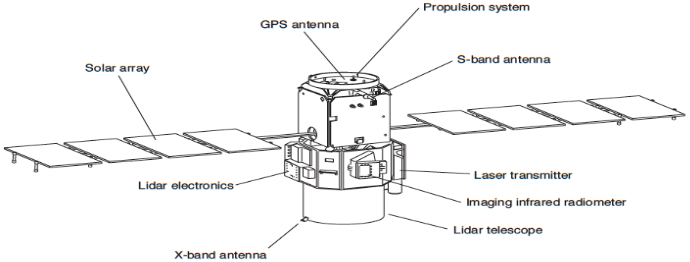
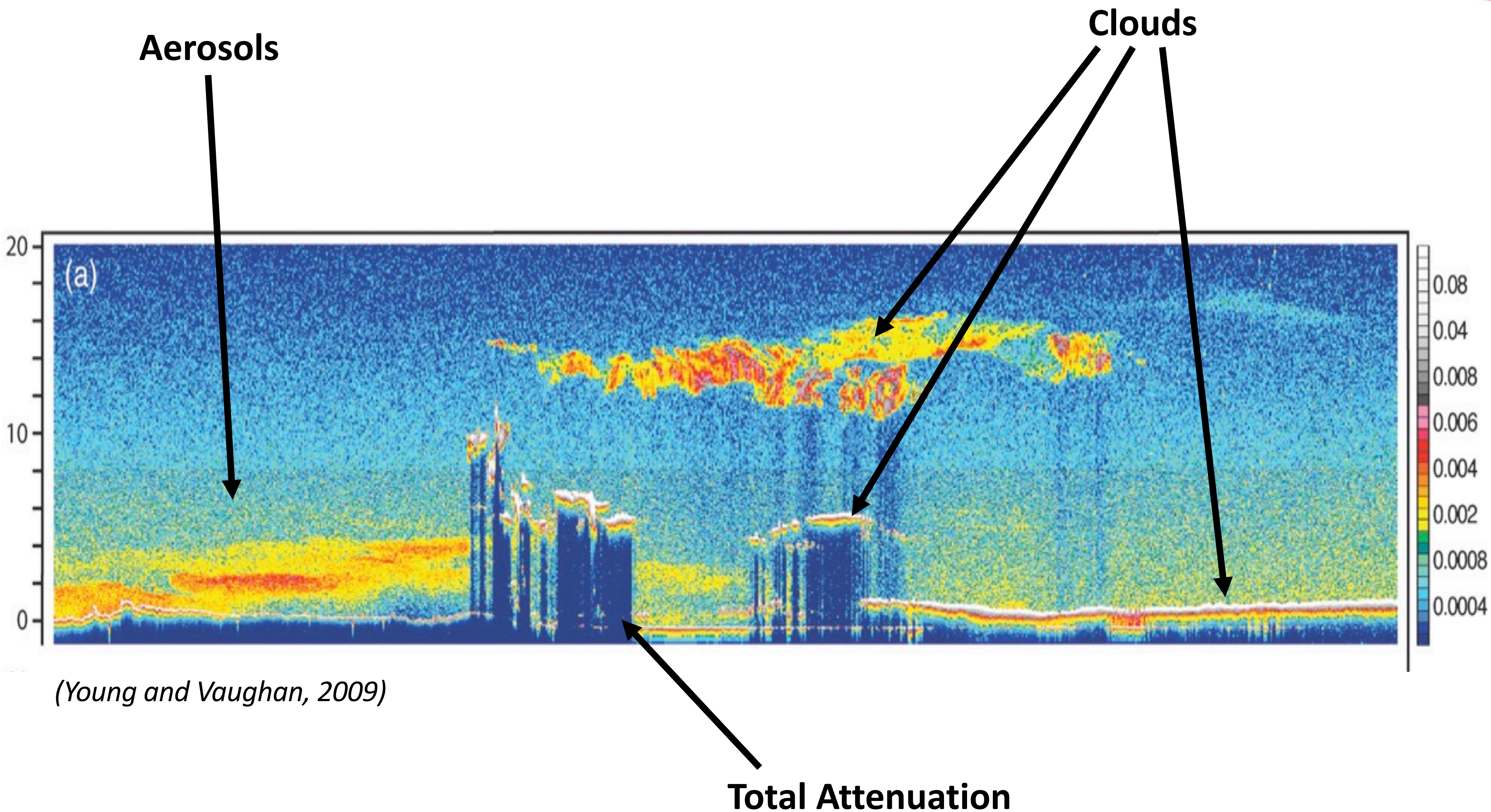


https://www-calipso.larc.nasa.gov

An example CALIOP curtain plot



(Young and Vaughan, 2009)

Examples of available data products

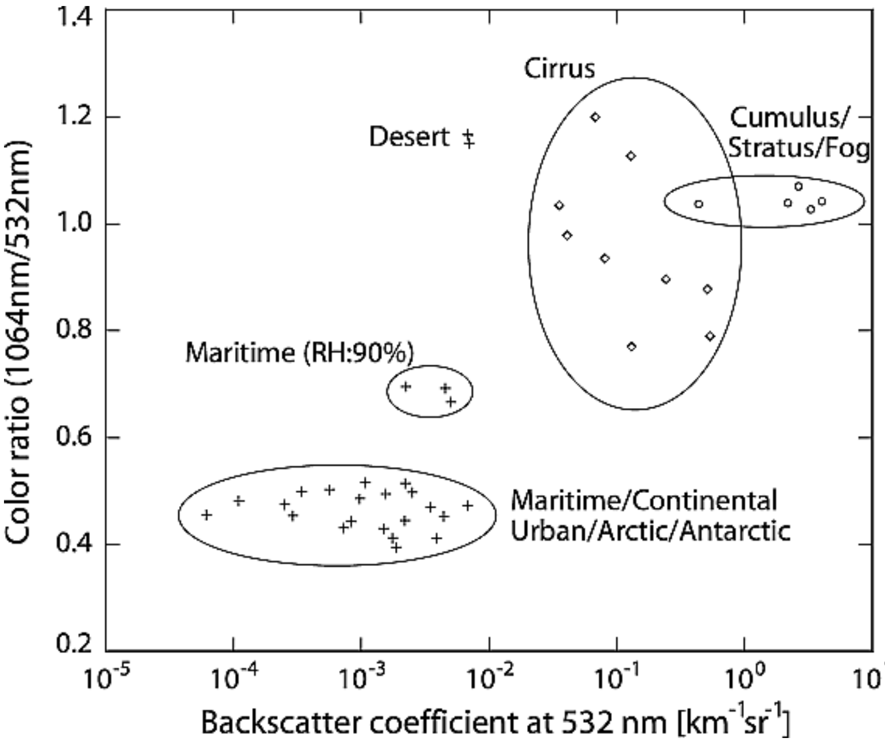
- Level 1
  - Calibration parameters, land/water mask, surface elevation, meteorological data (temperature, pressure, RH)
- Level 2
  - Layer: Aerosol and cloud
  - Profile: Aerosol and cloud
  - Vertical feature mask (VFM)
- Level 3
  - Stratospheric aerosol
  - Ice cloud
  - Cloud occurrence

Just a few CALIPSO parameters…

- ***Backscatter***: The amount of light scattered in the backward direction towards the lidar receiver (absorption is assumed, not measured)
- ***Extinction***: The total loss of light on the way from the lidar to the scattering volume and back (this is retrieved, not measured)
- ***Lidar ratio***: Extinction/backscatter (varies by feature and is assumed)
- ***Color ratio***: 1064 nm backscatter/532 nm backscatter
- ***Depolarization ratio***: Perpendicular component of backscatter/parallel component of backscatter
- ***Feature classification flag***: typing of each layer detected by CALIOP (e.g., cloud vs. aerosol, subtypes, cloud ice/water phase)

How does CALIOP discriminate between aerosols and clouds?

- Cloud-Aerosol Discrimination (CAD) Algorithm
- Performed on basis of statistical differences between spatial and optical properties of clouds and aerosols
  - 5D Probability density function (PDF) based approach:
    - Backscatter
    - Color ratio
    - Altitude
    - Depolarization ratio
    - Latitude
- Along with classification decision, PDF-based approaches can also assign a confidence level to each decision



(Vaughan et al. 2004)

- Clouds
  - Large backscatter coefficients and high color ratios
- Aerosols
  - Smaller backscatter coefficients and lower color ratios

Vertical Feature Mask (VFM)

- Describes vertical and horizontal distribution of cloud and aerosol layers observed by CALIOP
- Feature classification flag parameter is reported as a 16-bit integer
- Data are recorded in increments of 15 consecutive laser pulses (roughly equivalent to a distance of 5 km along the laser ground-track

- Parameters include:
  - Feature type
  - Ice/Water phase
  - Feature subtype
  - Horizontal averaging

CALIOP—Feature types

Value	Feature type
1	"Clear air"
2	Cloud
3	Aerosol
4	Stratospheric feature
5	Surface
6	Subsurface
7	No signal (totally attenuated)

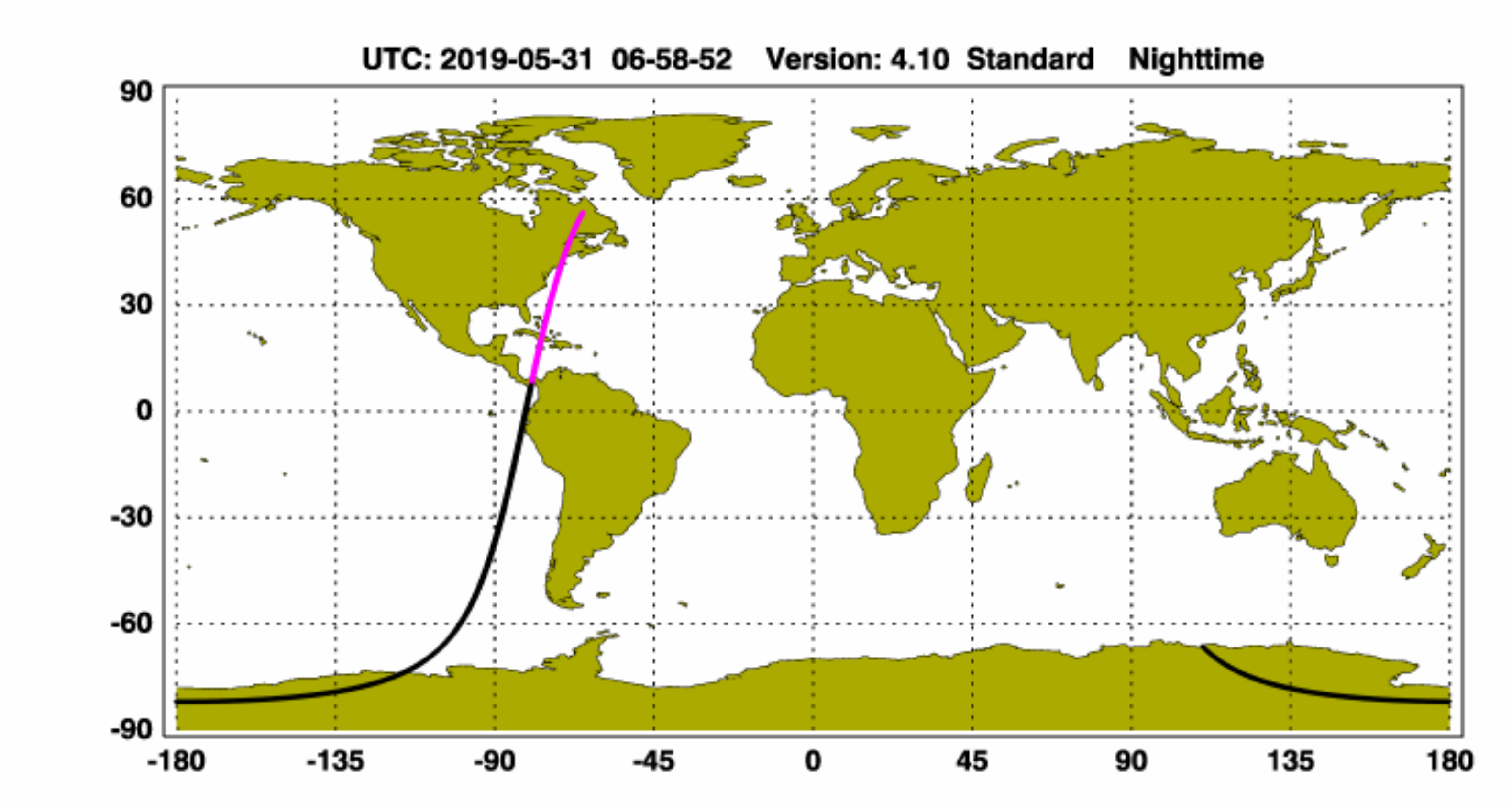
(Marchand et al. 2008)

CALIOP – Feature subtypes

Aerosol	Cloud
Not determined	Low overcast, transparent
Clean marine	Low overcast, opaque
Dust	Transition stratocumulus
Polluted continental	Low, broken cumulus
Clean continental	Altocumulus (transparent)
Polluted dust	Altostratus (opaque)
Smoke	Cirrus (transparent)
Other	Deep convective (opaque)

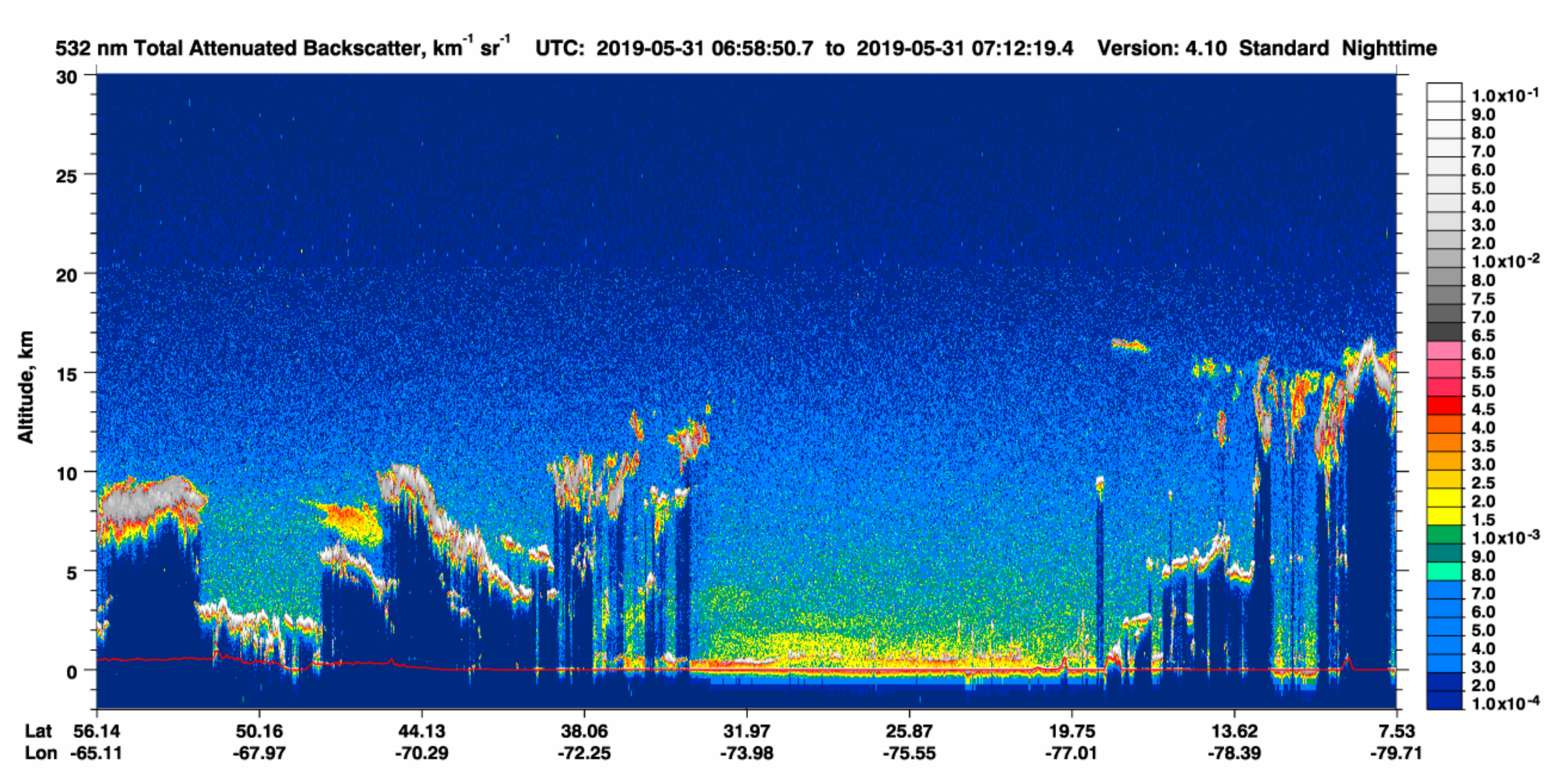
(CALIPSO Data Products Catalog)

May 31st, 2019: CALIOP track



(https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/)

May 31st, 2019: 532 nm Backscatter



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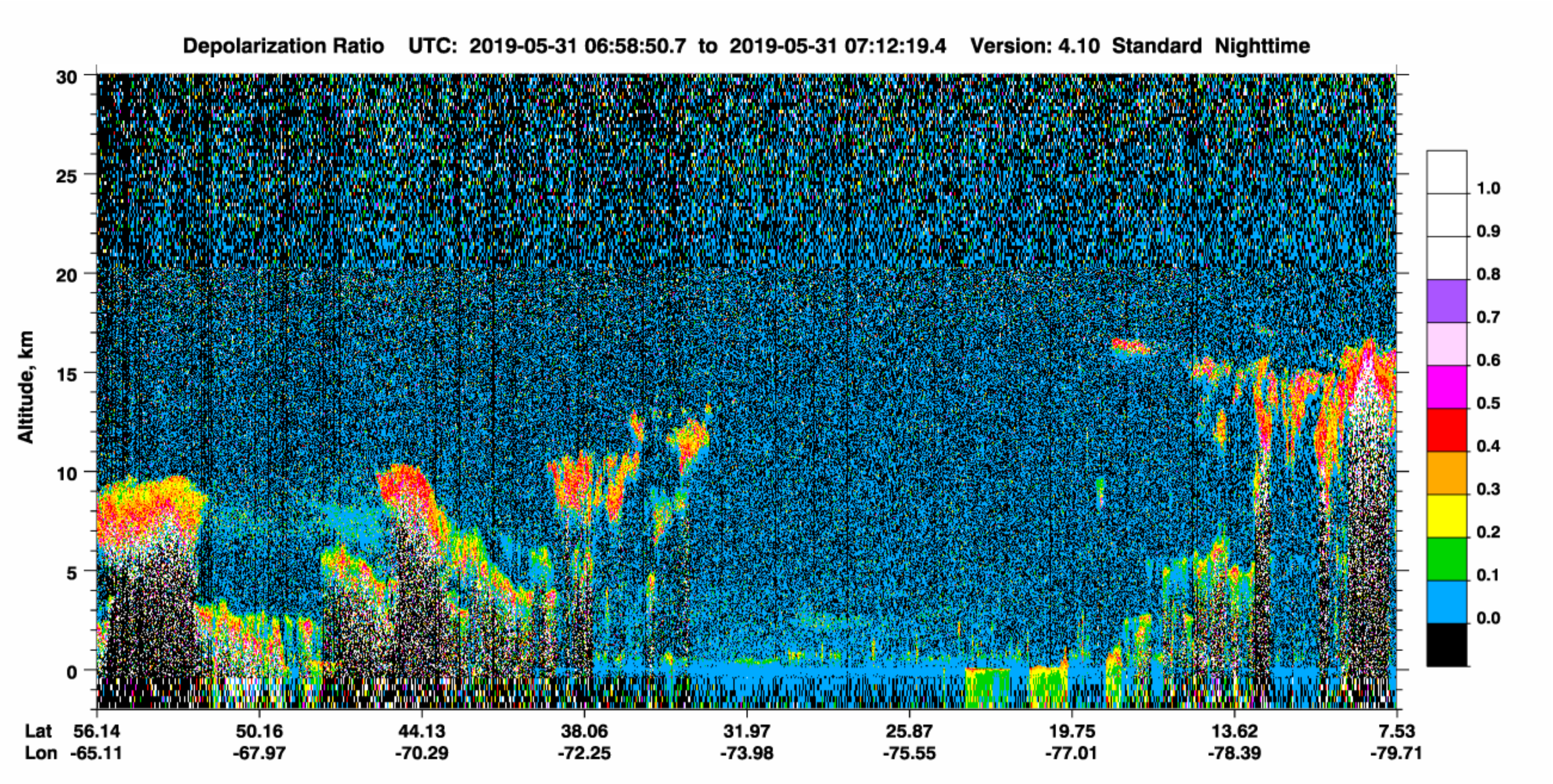
May 31st, 2019: Depolarization Ratio



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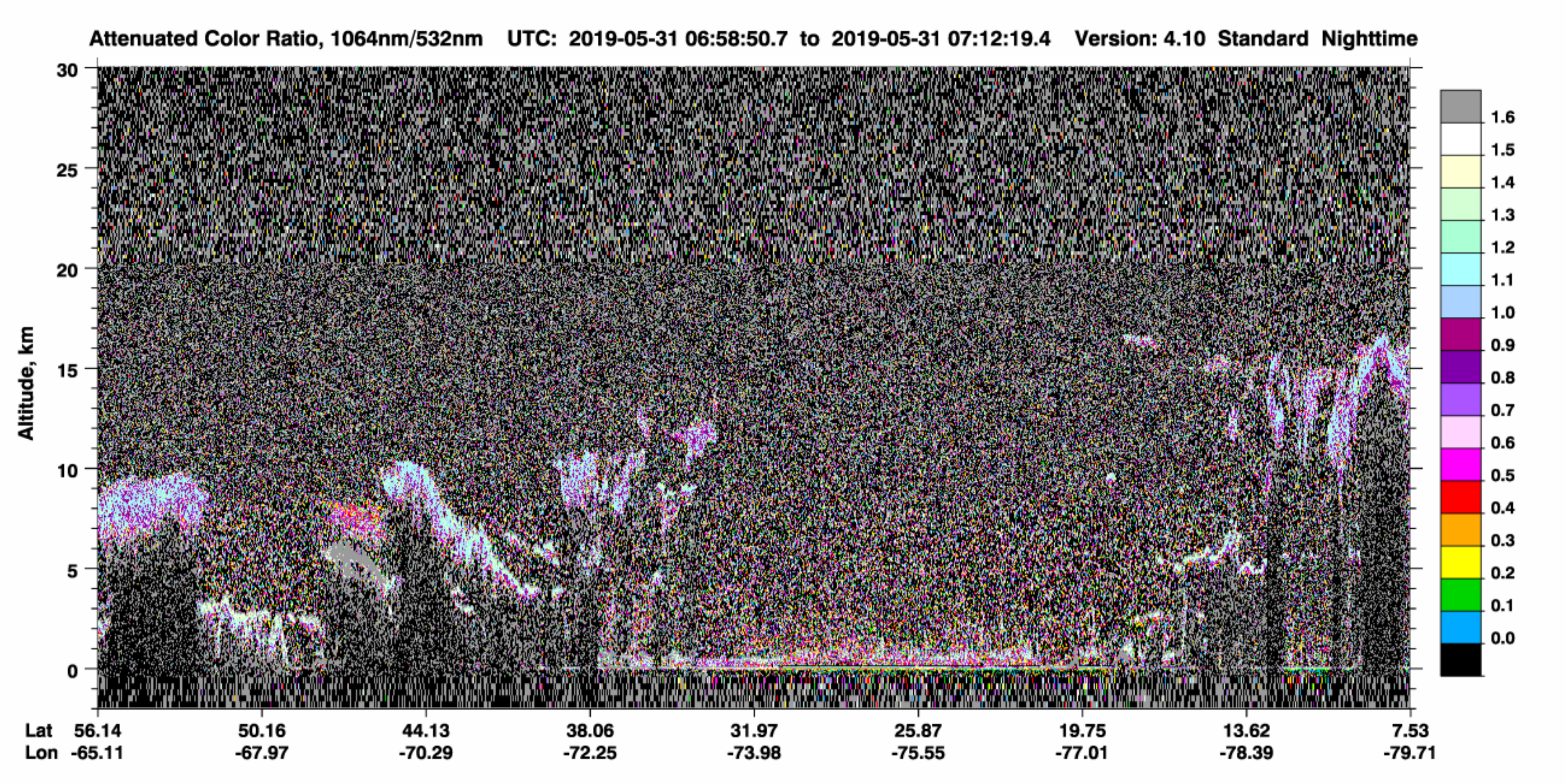
May 31st, 2019: Color Ratio



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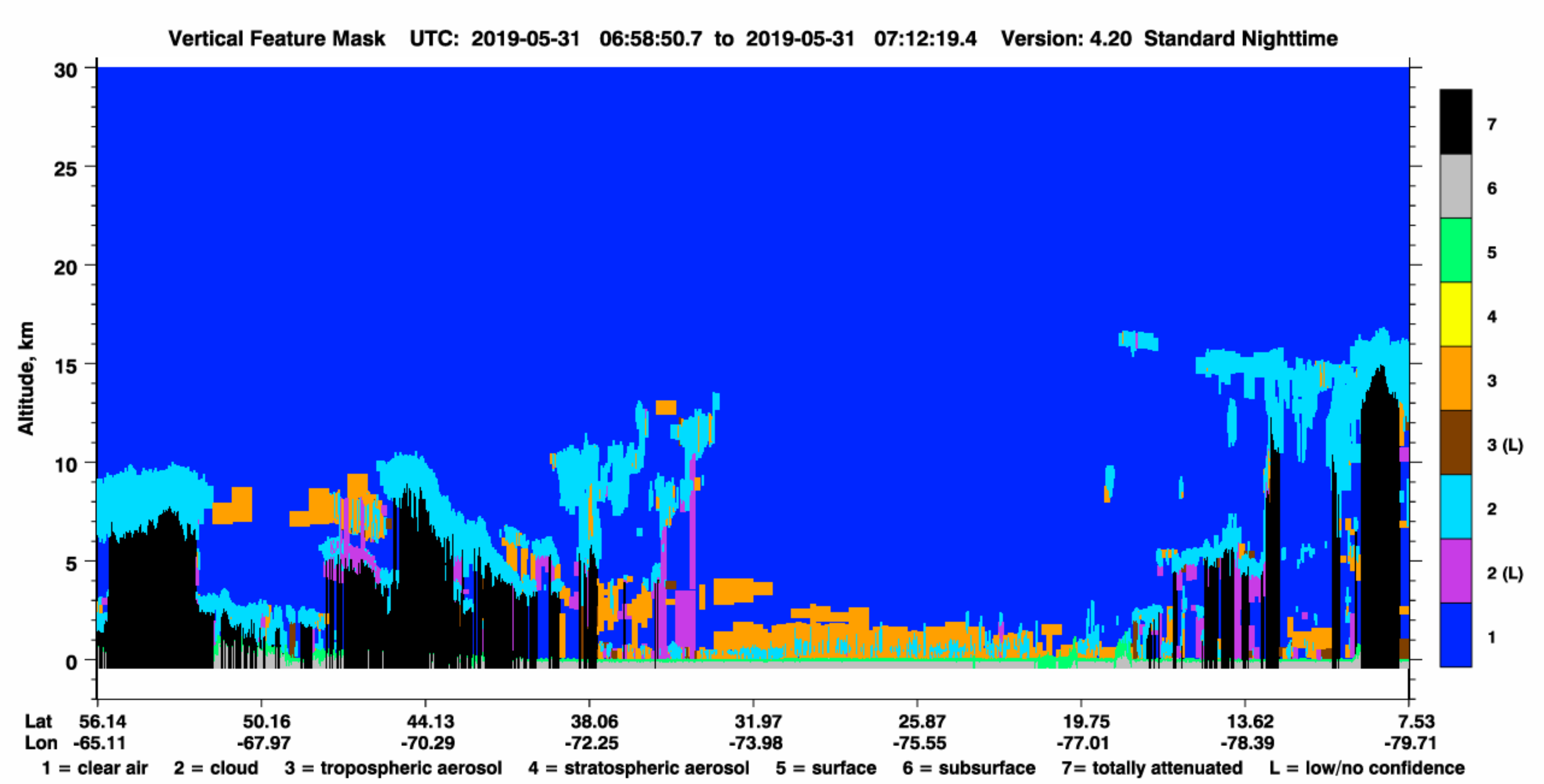
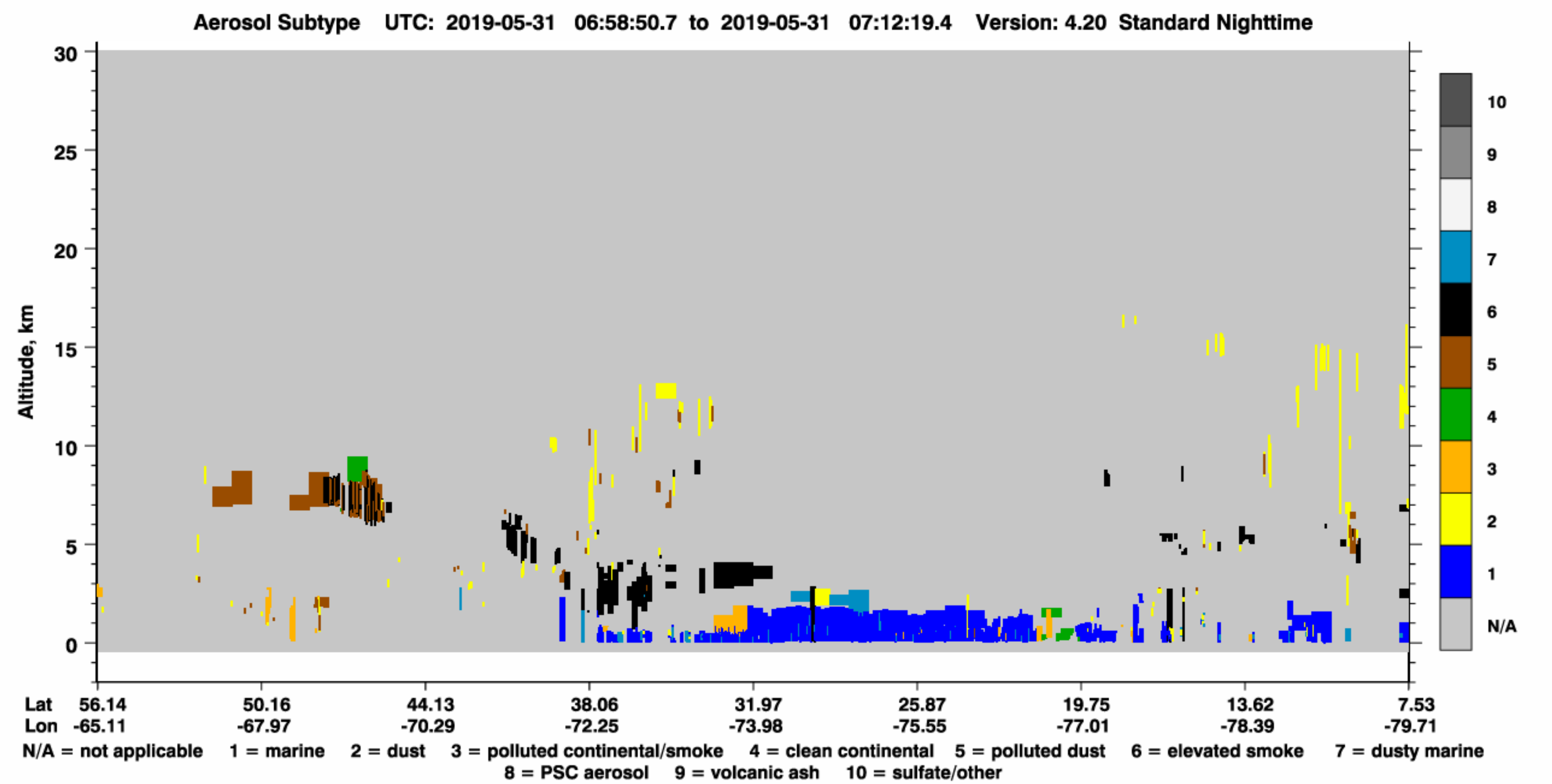
May 31st, 2019: VFM



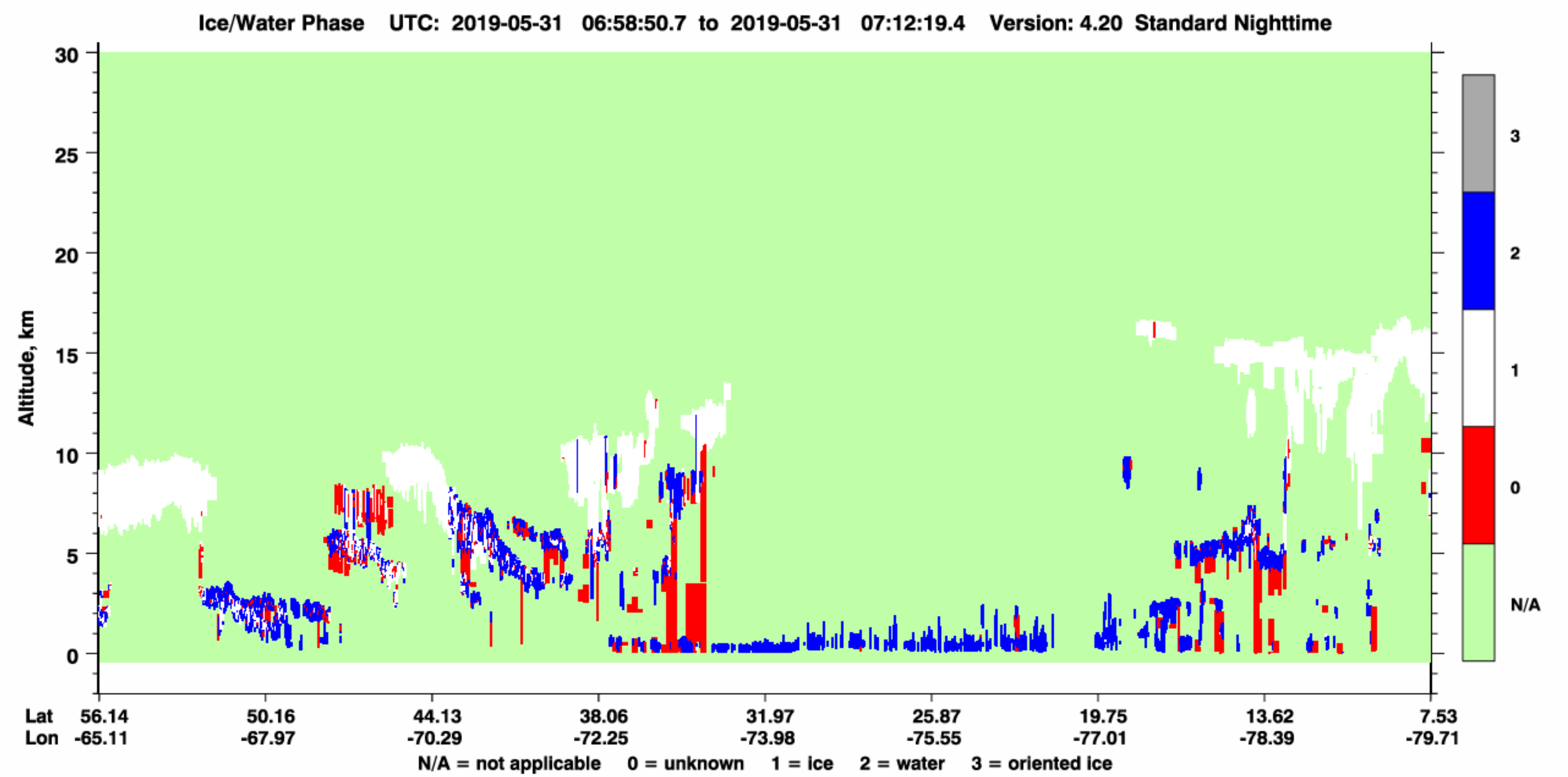
(https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/)

May 31st, 2019: Aerosol Subtype



(https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/)

May 31st, 2019: Ice/Water Phase



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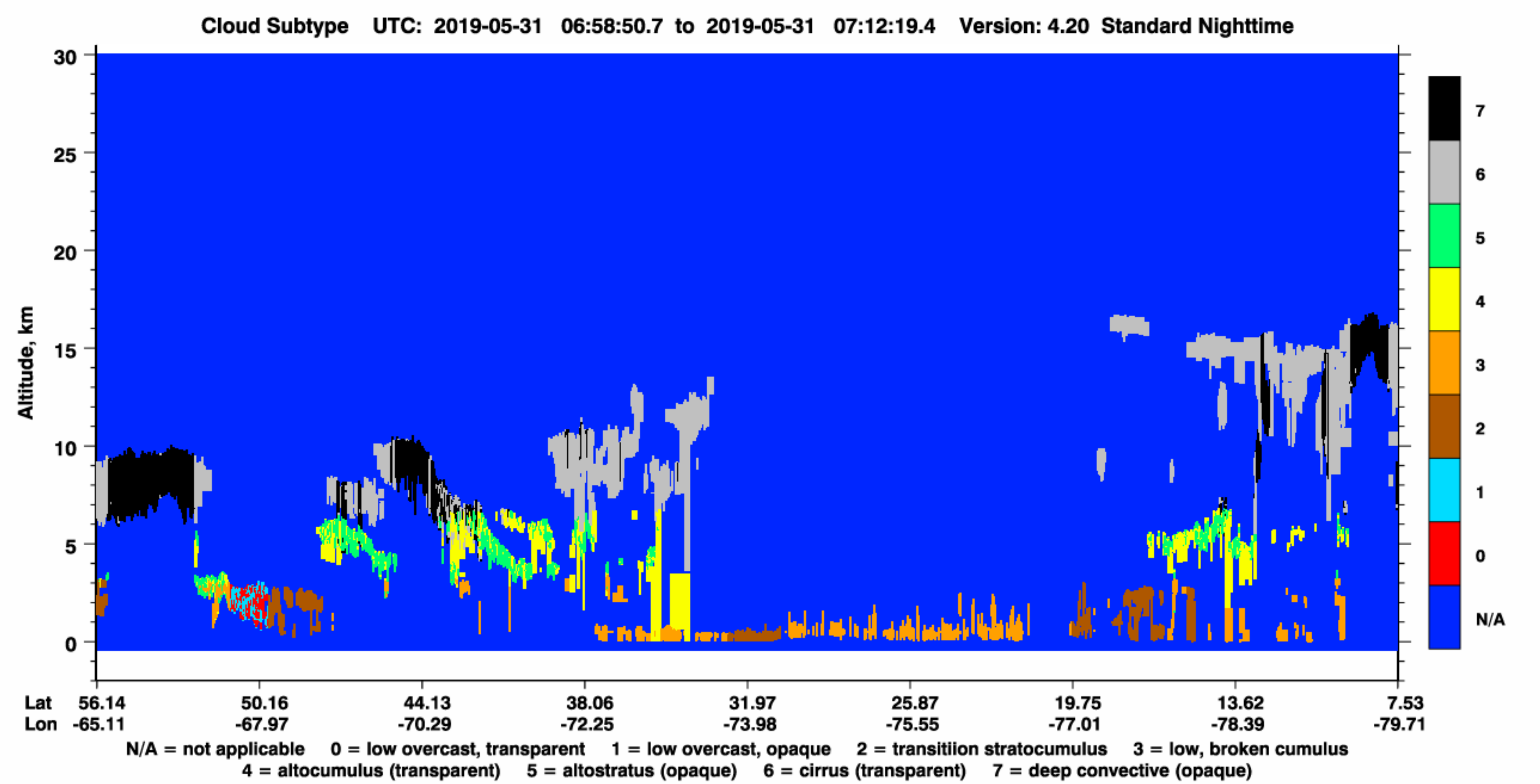
May 31st, 2019: Cloud Subtype



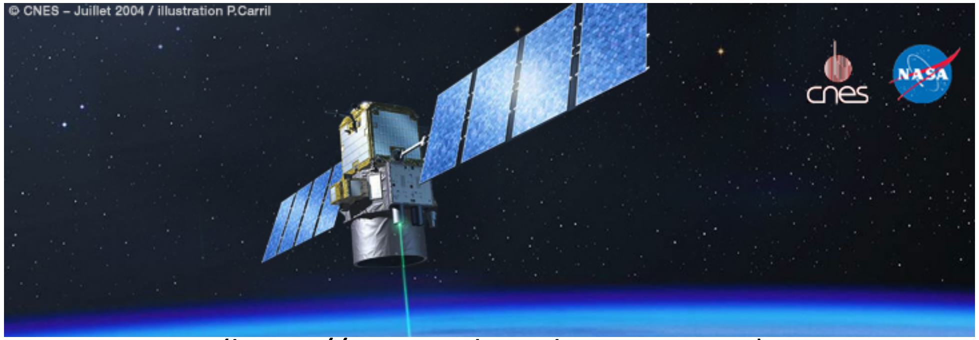
(https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/)

Obtaining & Viewing CALIPSO data

(https://www-calipso.larc.nasa.gov)

- Data can be downloaded from NASA Langley's ASDC at https://eosweb.larc.nasa.gov

- Images can be browsed at http://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/

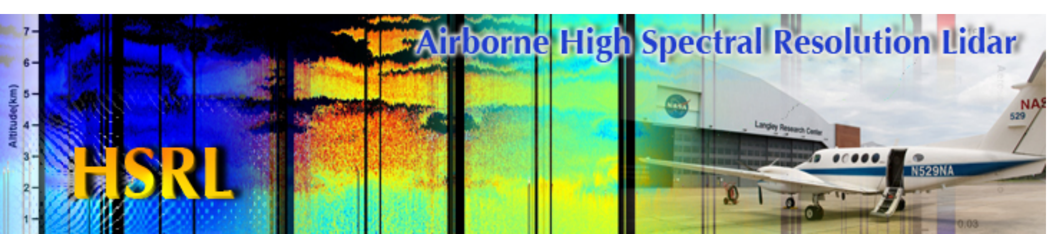


(https://www-calipso.larc.nasa.gov)

Lidars at Langley: High Spectral Resolution Lidar (HSRL)

- Specific form of elastic backscatter lidar
- Takes advantage of spectral distribution of lidar return signal to discriminate aerosol returns from molecular returns
- Estimates aerosol extinction and backscatter coefficients independently
- Significantly reduced uncertainty
- Likely the future of lidars

Participation in several field campaigns:



(https://science.larc.nasa.gov/hsrl/)

Future of space-based lidar remote sensing

(https://earth.esa.int/web/guest/missions/esa-future-missions/earthcare)

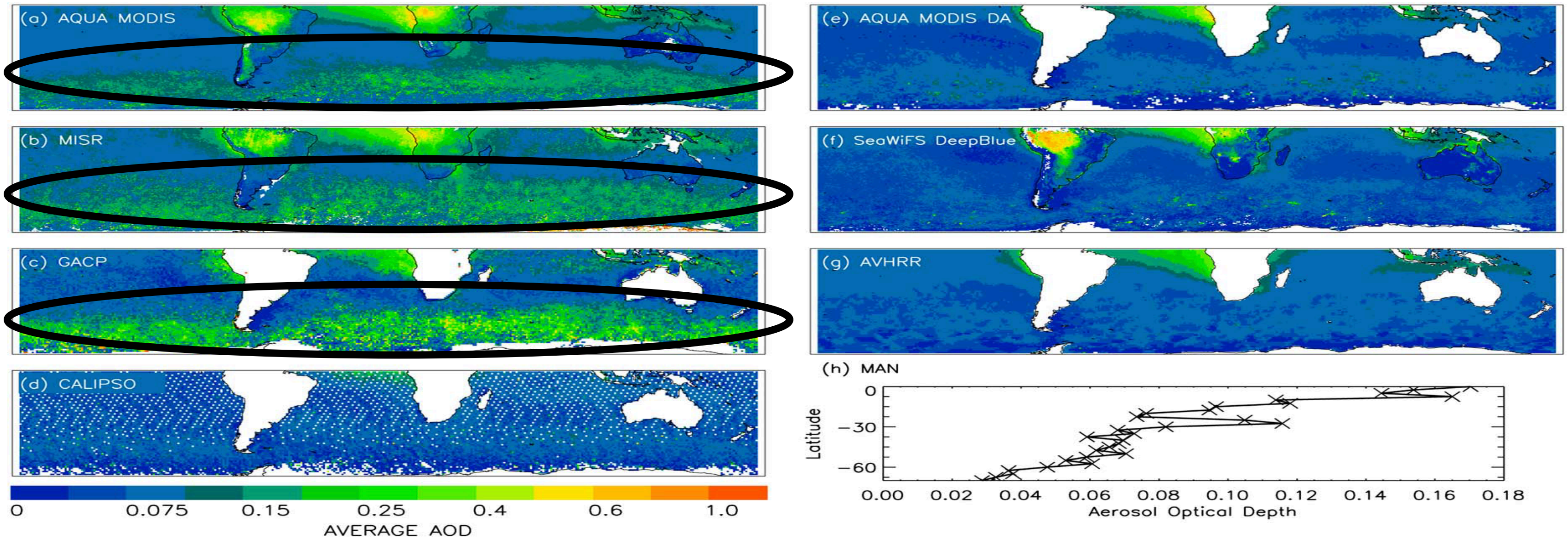
- EarthCARE
  - Earth Clouds, Aerosols, and Radiation Explorer
  - Upcoming joint European/Japanese satellite mission
  - Scheduled for launch in 2021
  - Payload consists of four instruments, including a lidar (HSRL)
- A-CCP study
  - Aerosols and Clouds, Convection, and Precipitation
  - NASA satellite mission concept/formulation
  - Collaboration between several NASA centers, primarily Goddard, Langley, and JPL
  - 2018-2021

CALIPSO science applications

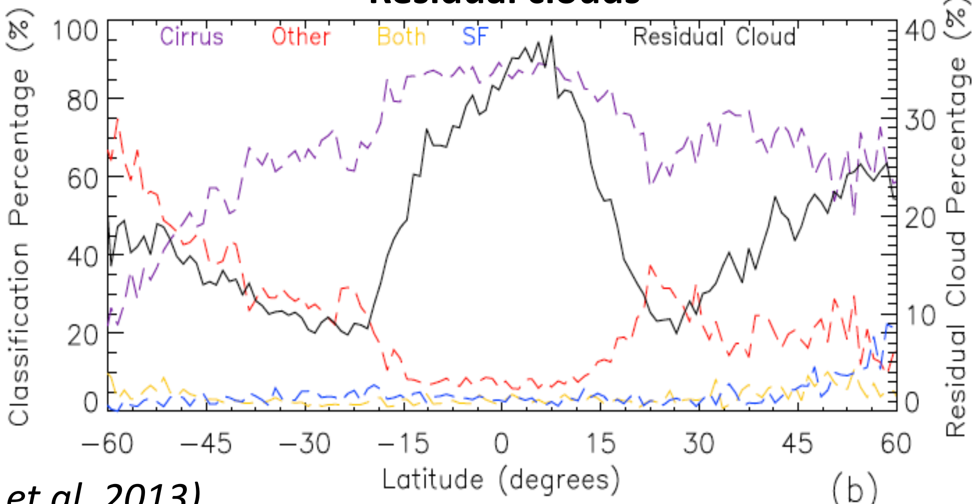
- Research topics:
  - Cloud contamination in passive satellite retrievals (2013)
  - Limitations of $PM_{2.5}$/satellite AOD relationship (2014)
  - Trends in aerosol vertical distribution (2016)
  - Aerosol detection limits (2018)
  - Deriving $PM_{2.5}$ from lidar measurements (2019)

Cloud contamination in passive satellite retrievals (2013)

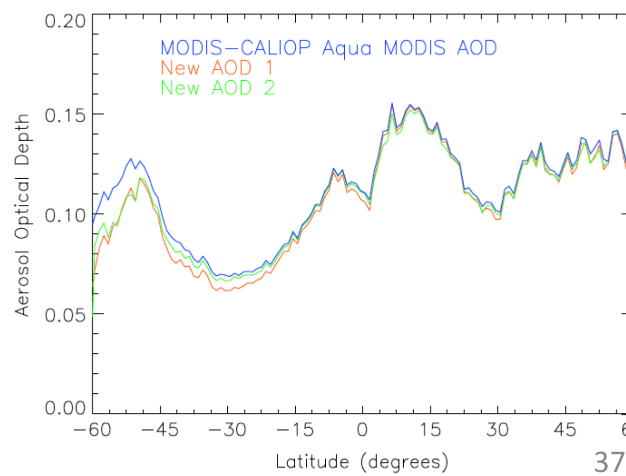
Enhanced AOD in Southern Oceans for some passive satellite sensors, but not others…



Residual clouds



Zonal AOD distribution



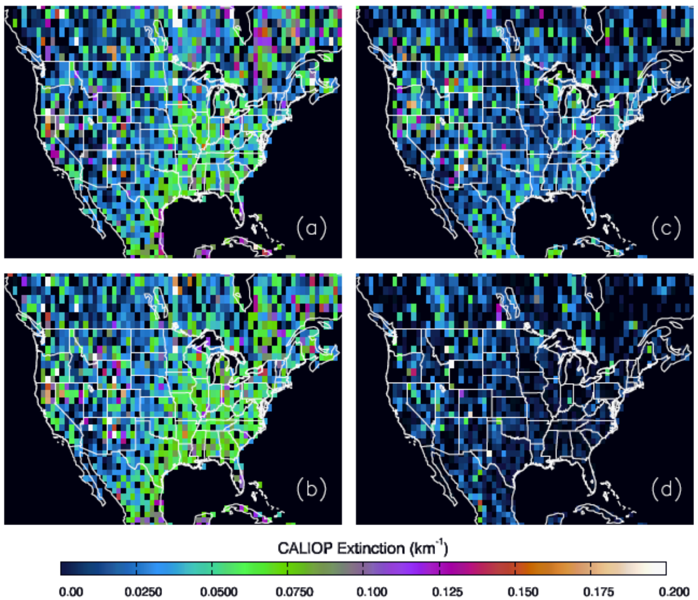
(Toth et al. 2013)

Limitations of $PM_{2.5}$/satellite AOD relationship (2014)

1. Representativeness of surface-based measurements to aerosol particle presence within the full column

0-500m

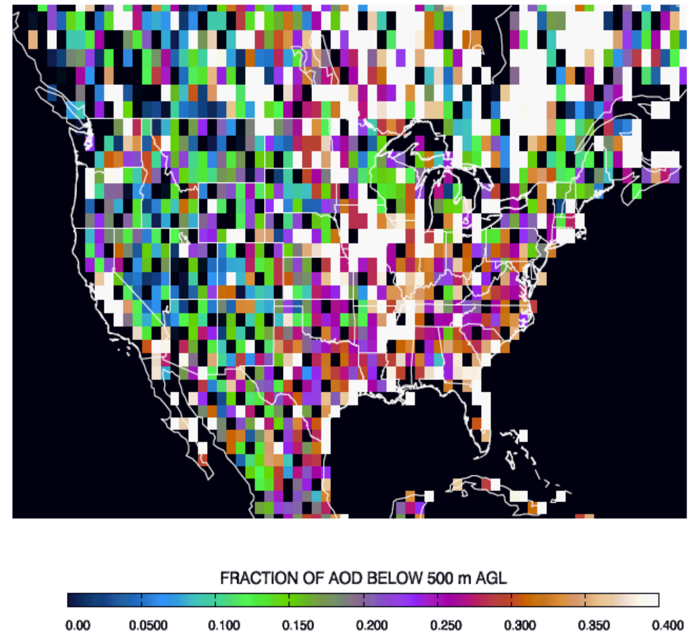
500-1500m



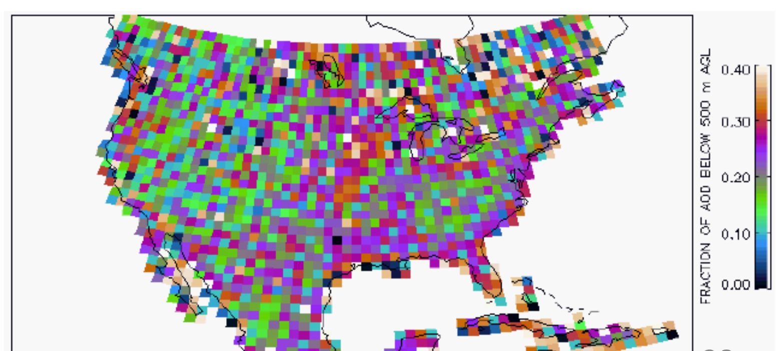
1500-2500m

2500-3500m

Fraction of AOD below 500 m AGL



- Aerosol particle distributions tend to be more concentrated near surface in east and more diffuse in west
- Values generally less than 40% across CONUS
- Higher fractions for eastern CONUS than western CONUS



2006-2011

(Toth et al. 2014)

Limitations of $PM_{2.5}$/satellite AOD relationship (2014)

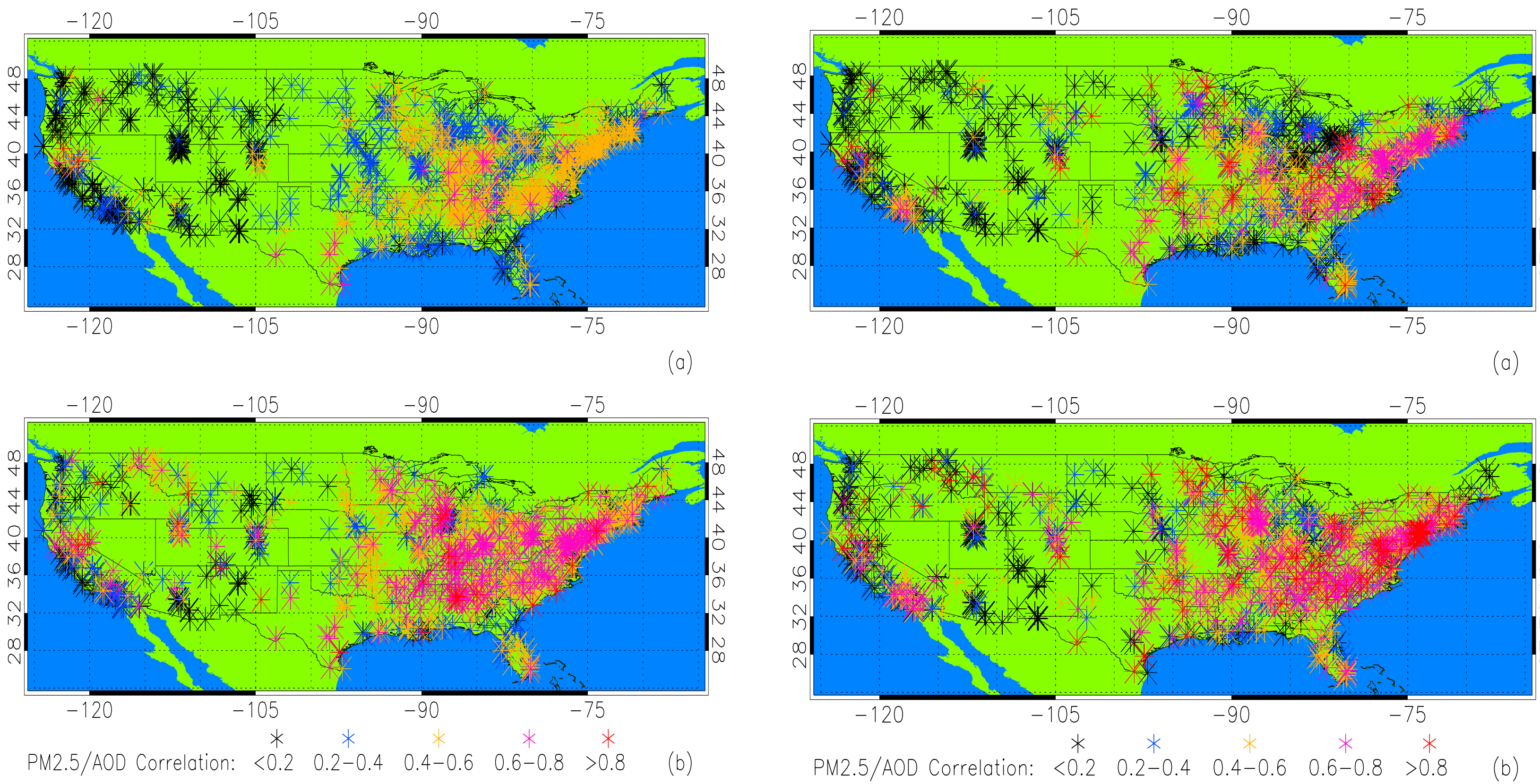
2. Quality of passive satellite AOD retrievals

- Spatial collocation: 1° latitude/longitude
- Temporal collocation: 1 day

Terra MODIS | **Terra MISR**

Operational

Data Assimilation



- Correlations increase from the operational to data assimilation analyses, but remain low

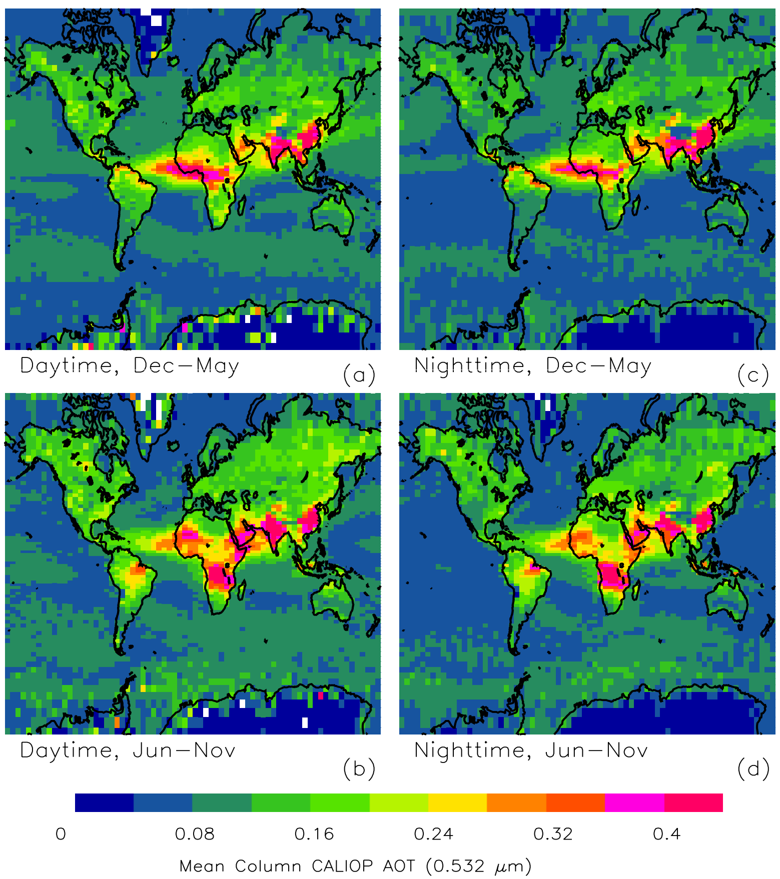
(Toth et al. 2014)

Trends in aerosol vertical distribution (2016)

Mean state of aerosol vertical distribution through the atmosphere

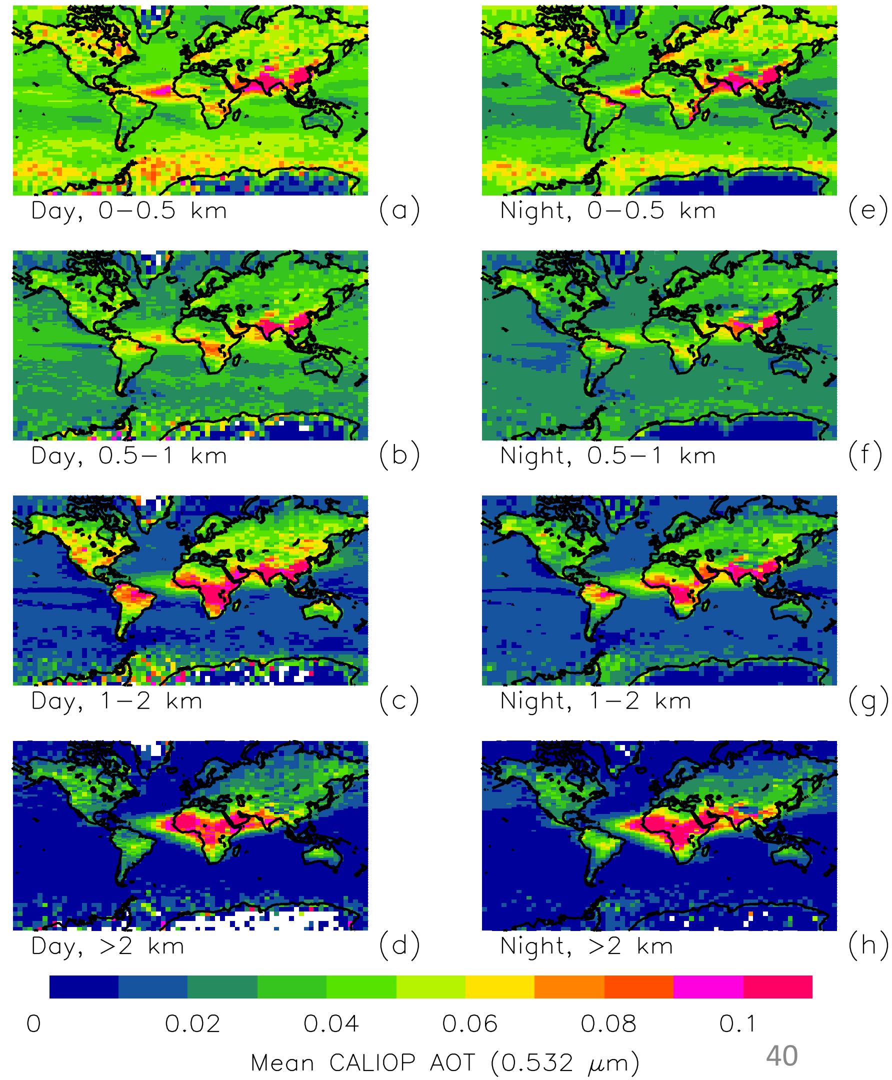
Column AOD

Daytime **Nighttime**



AOD by altitude range

Daytime **Nighttime**



(Toth et al. 2016)

Trends in aerosol vertical distribution (2016)

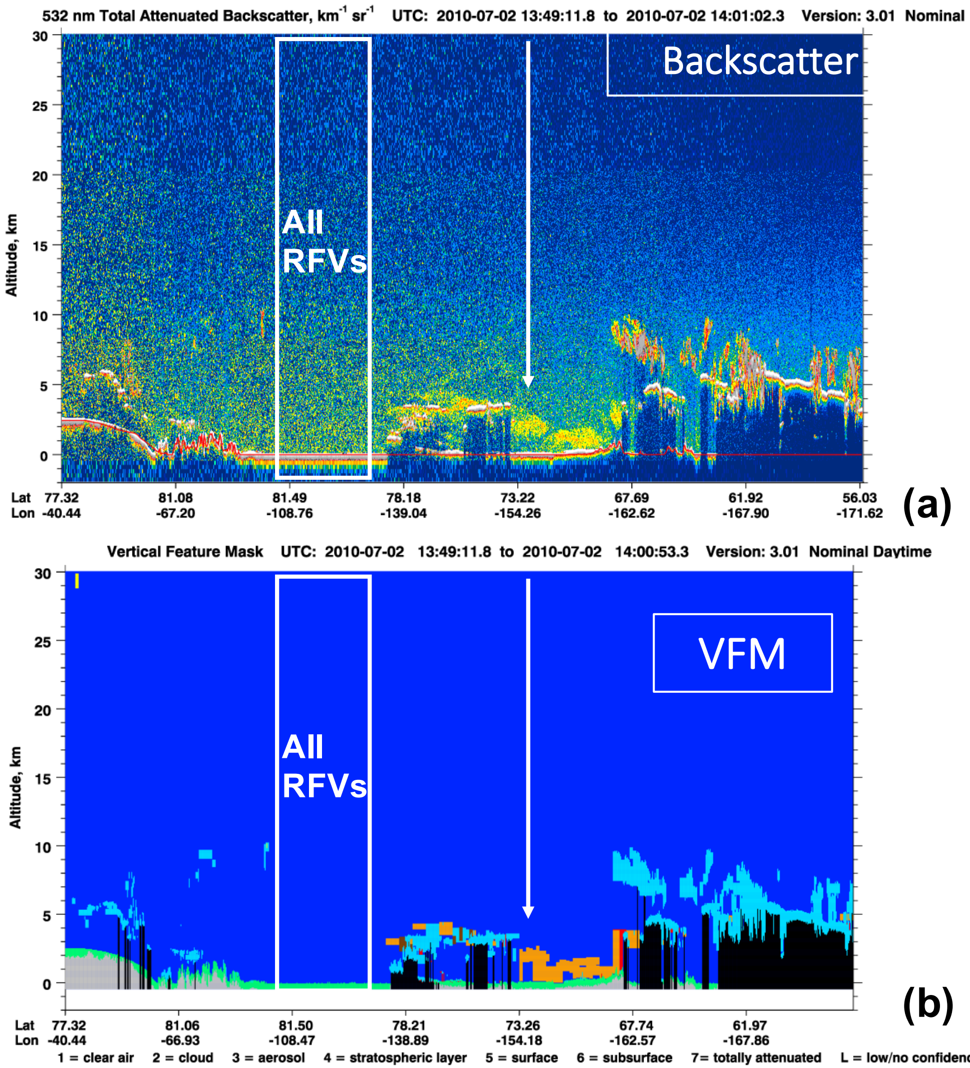
Are changes in column-integrated aerosol loading most common near the surface or at other altitudes?

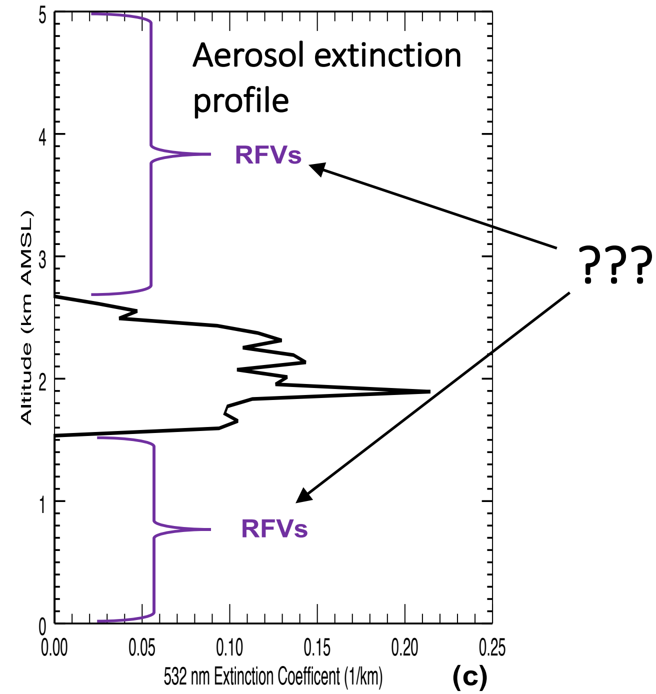
- Daytime positive trend
  - 0.0-0.5 km and 0.5-1.0 km AGL
- Nighttime negative trend
  - 1.0-2.0 km and > 2.0 km AGL

- **Increasing** trends → India and Southern Africa
- **Decreasing** trends → all other regions of focus

(Toth et al. 2016)

Aerosol detection limits (2018)



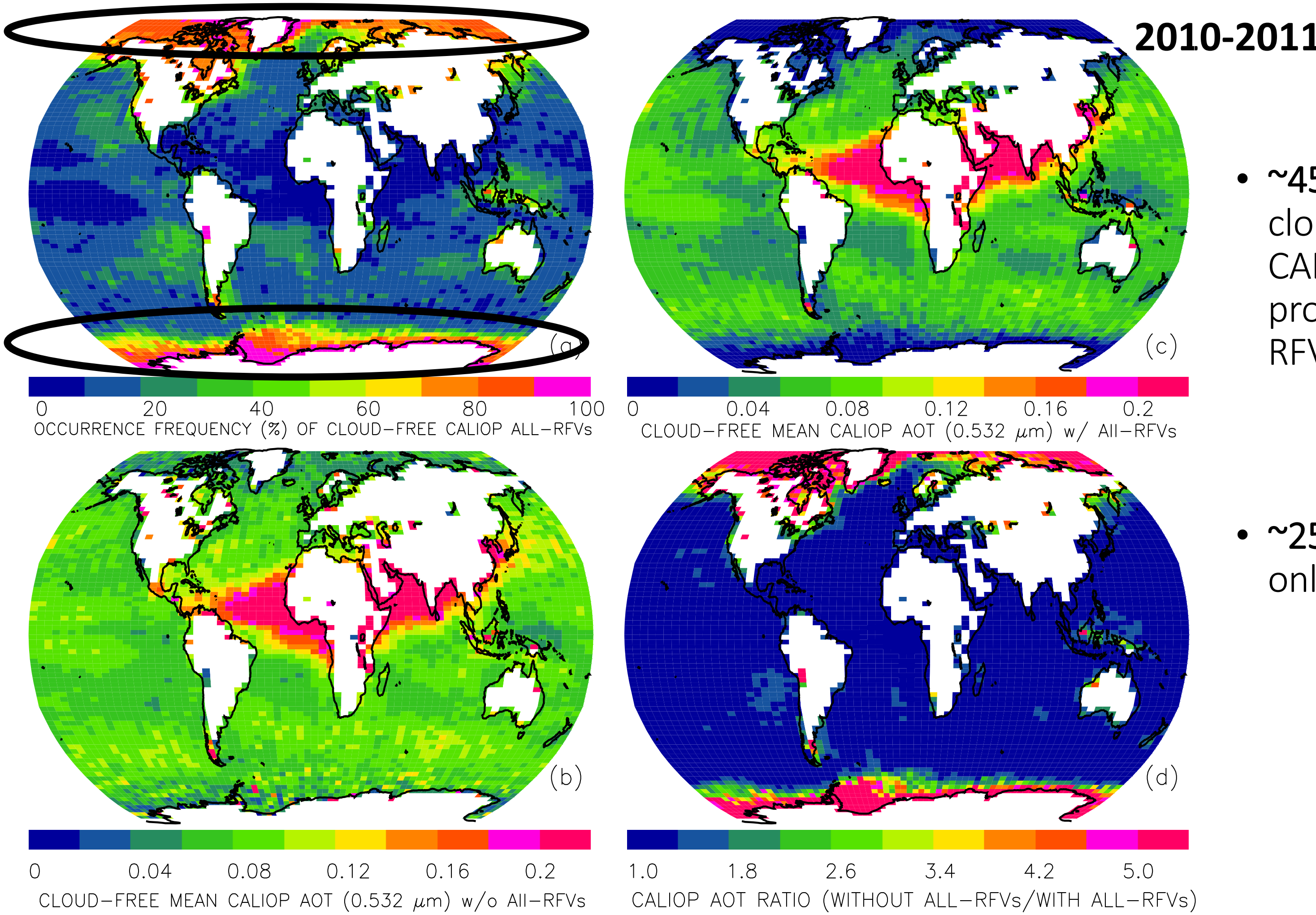


- Range bins where no aerosol is detected or the extinction retrieval fails, are assigned fill values → **retrieval fill values, or RFVs**
- If no aerosol is detected anywhere in column, it will consist entirely of RFVs **→All-RFV profiles**

(Toth et al. 2018)

Aerosol detection limits (2018)

Where do All-RFV CALIOP profiles occur most frequently?

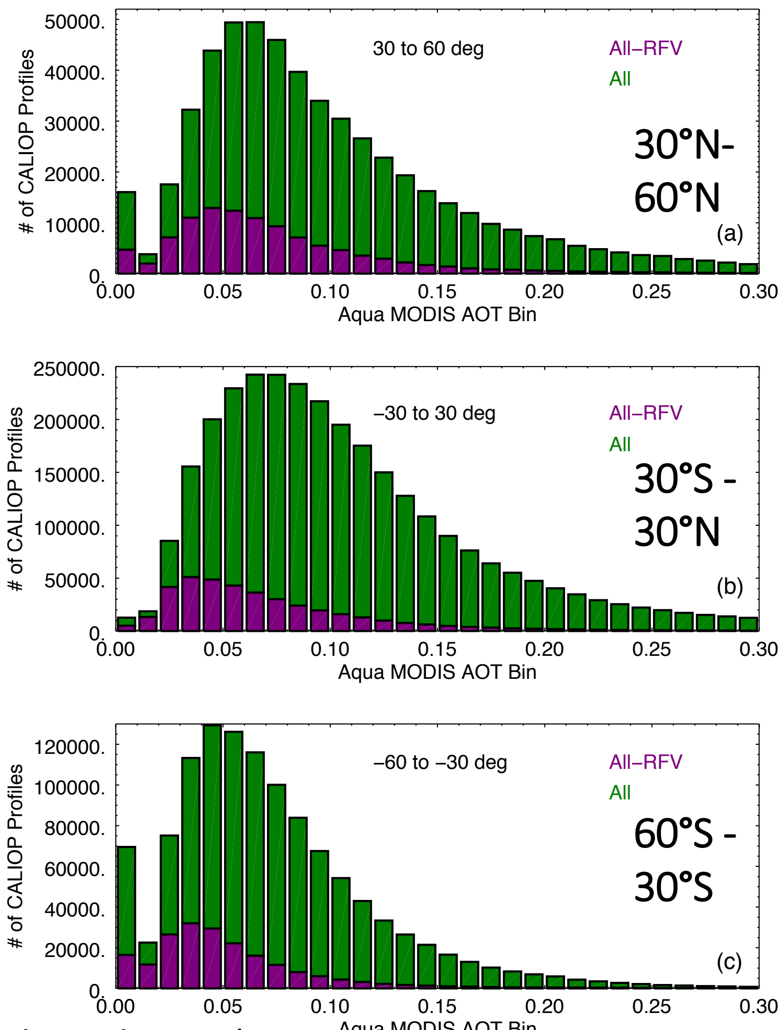


- **~45%** of the global cloud-free daytime CALIOP L2 aerosol profile dataset are All-RFV profiles
- **~25%** for global oceans only

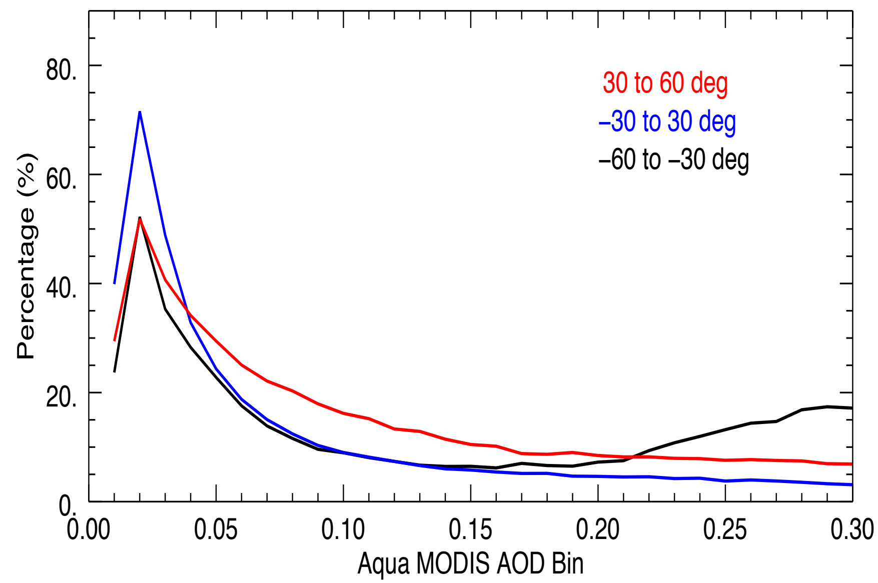
(Toth et al. 2018)

Distribution of MODIS AODs for collocated CALIOP All-RFV profiles (2010-2011)

All-RFV All



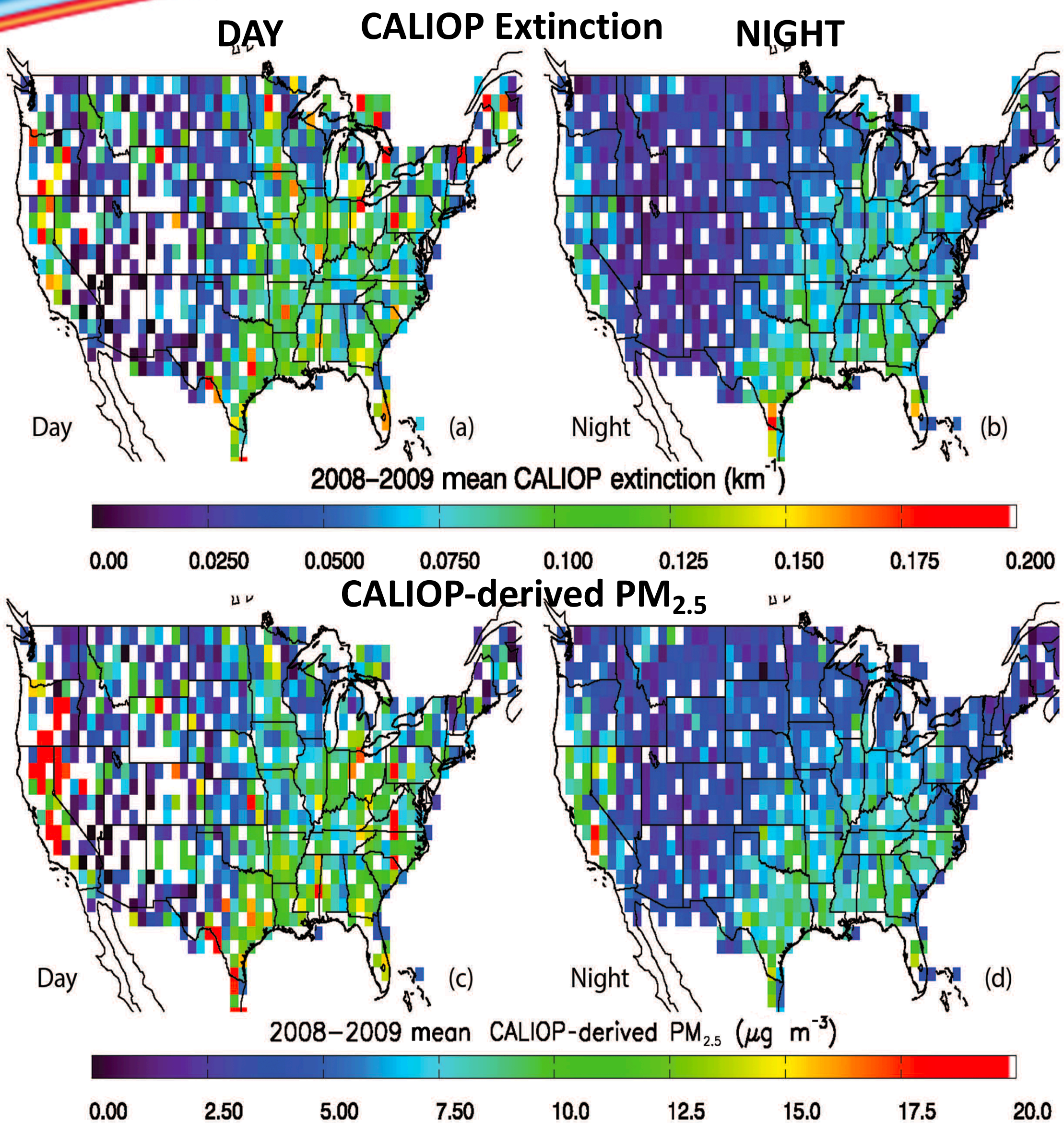
- Collocation: MODIS AOD within 8 km of temporal midpoint of CALIOP



- Modal MODIS AODs for All-RFV profiles are ~0.03-0.04
- The 0.01-0.02 MODIS AOD bin exhibits the largest underestimation percentage that lowers toward higher MODIS AODs

(Toth et al. 2018)

Deriving $PM_{2.5}$ from lidar measurements (2019)



(Toth et al. 2019)

Algorithm

$$C_{m2.5} = \frac{\beta \text{ x } \phi \text{ x } 1000}{(a_{scat} \text{ x } f_{rh} + a_{abs})}$$

β → CALIOP extinction coefficient
C_m → PM mass concentration
a_{scat} → mass scattering efficiency
a_{abs} → mass absorption efficiency
ϕ → $PM_{2.5}$ to PM_{10} ratio
f_{rh} → hygroscopic growth factor

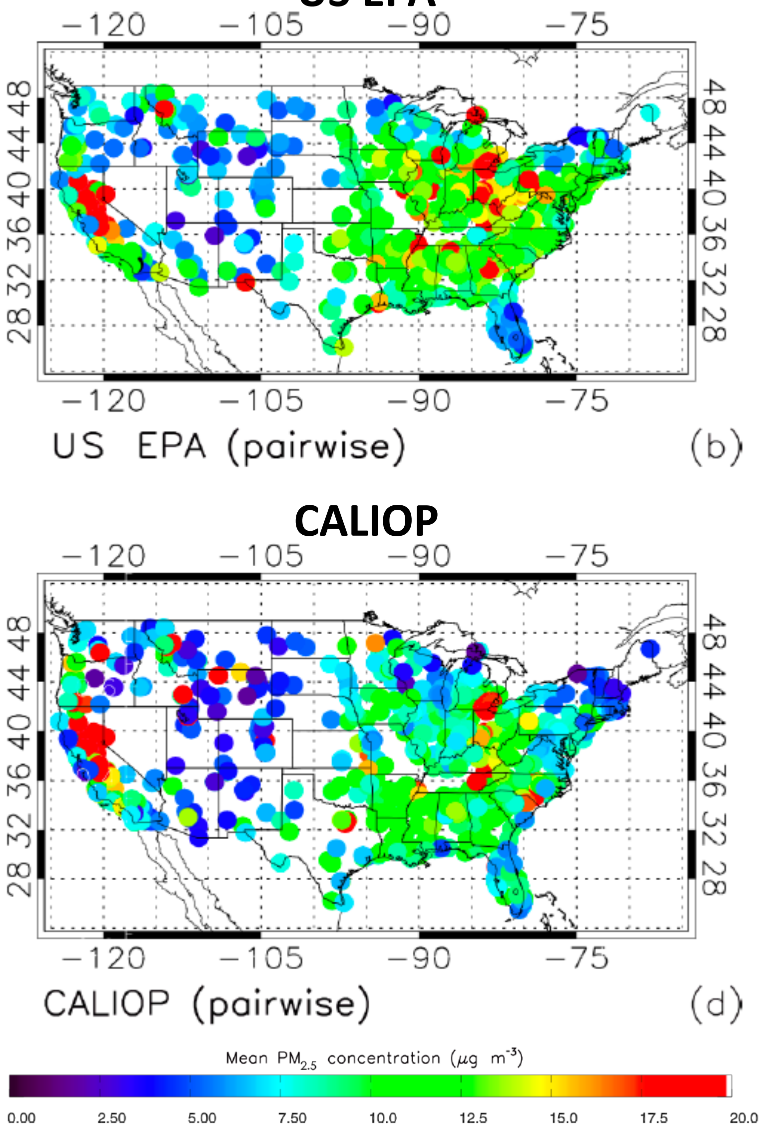
- Spatial patterns match well
- Day/night differences: Anthropogenic activities and/or solar radiation contamination (daytime noise)

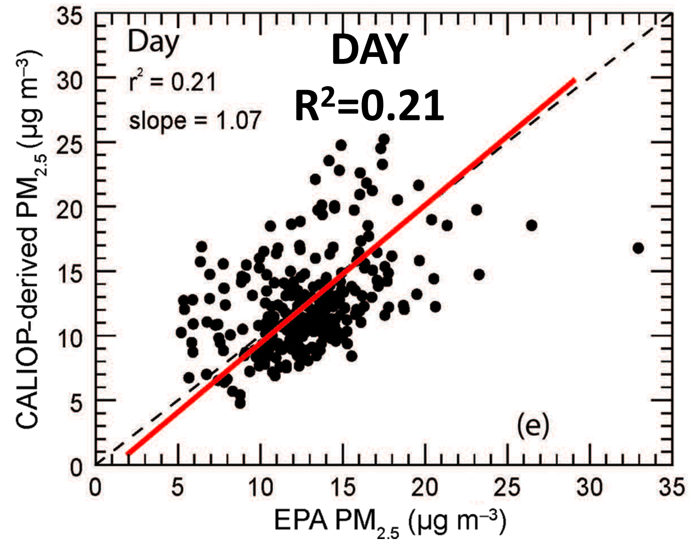
Deriving $PM_{2.5}$ from lidar measurements (2019)

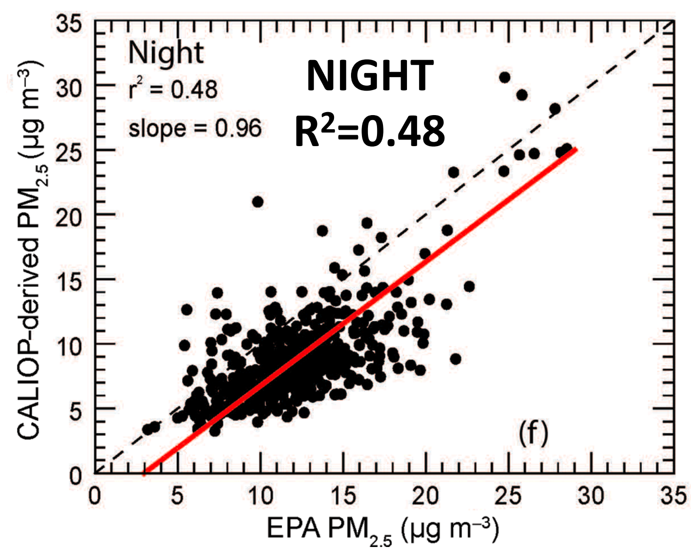
Validation efforts

US EPA

CALIOP





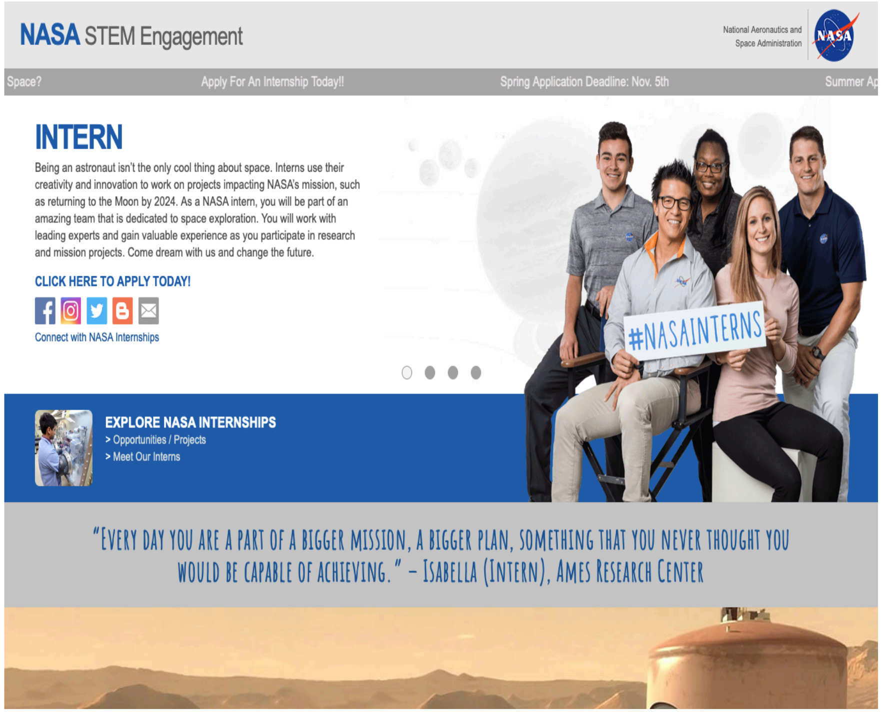


(Toth et al. 2019)

Getting Involved: Internship Opportunities at NASA

- https://intern.nasa.gov
- Eligibility requirements:
  - U.S. Citizen
    Cumulative 3.0 GPA (on a 4.0 scale)
    Full-time students (high school through graduate)
    Enrollment in a degree granting institution
    16 years of age at the time of application
- Three sessions:
  - Fall: Late August/early September to mid-December (16 weeks)
  - Spring: Mid-January to early May (16 weeks)
  - Summer: Late May/early June to August (10 weeks)

- Upcoming deadlines:
  Spring 2020: November 5th
  Summer 2020: March 8th
  Fall 2020: July 6th



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- https://science.larc.nasa.gov/hsrl/
- https://earth.esa.int/web/guest/missions/esa-future-missions/earthcare
- www.fickr.com; www.picryl.com

THANK YOU!

QUESTIONS?

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