Biomass Burning Aerosol Distributions over the Southeastern Atlantic Ocean measured by CALIOP and the NASA LaRC airborne High Spectral Resolution Lidar-2

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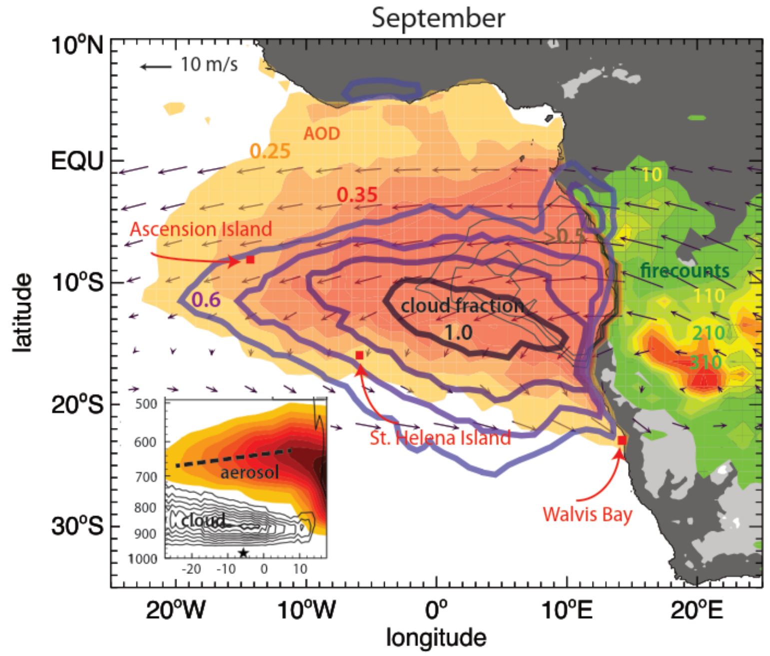
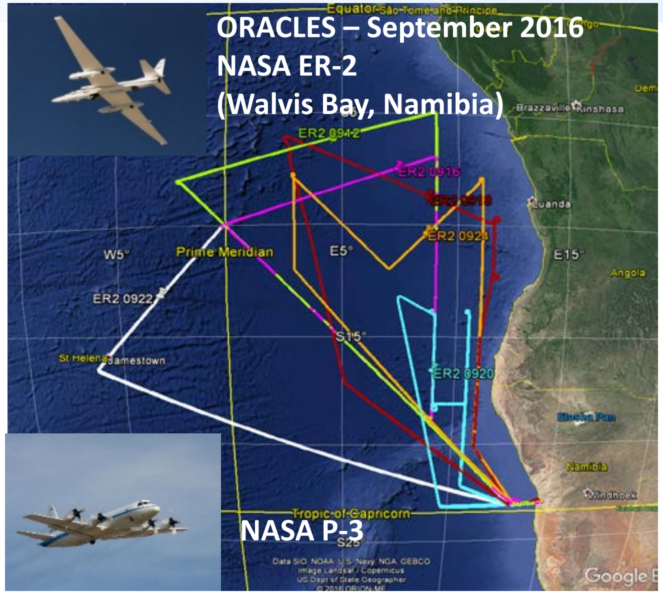
AEROCOM Meeting, October, 2018

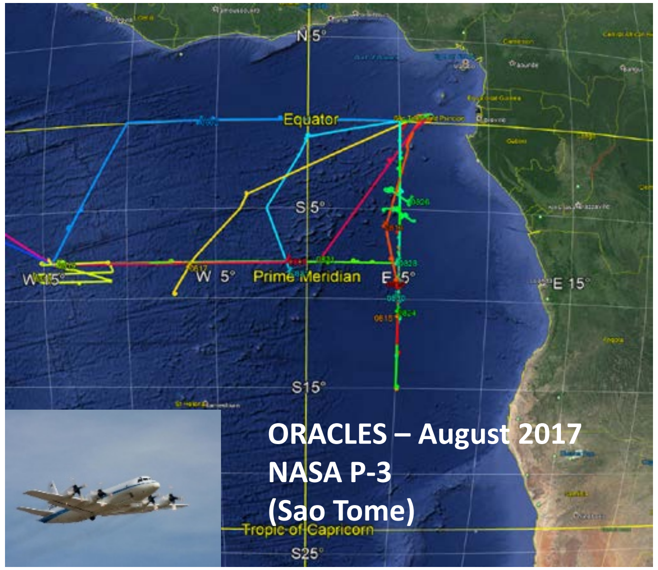
NASA ORACLES Mission Studying Aerosol and Clouds over Southeast Atlantic Ocean

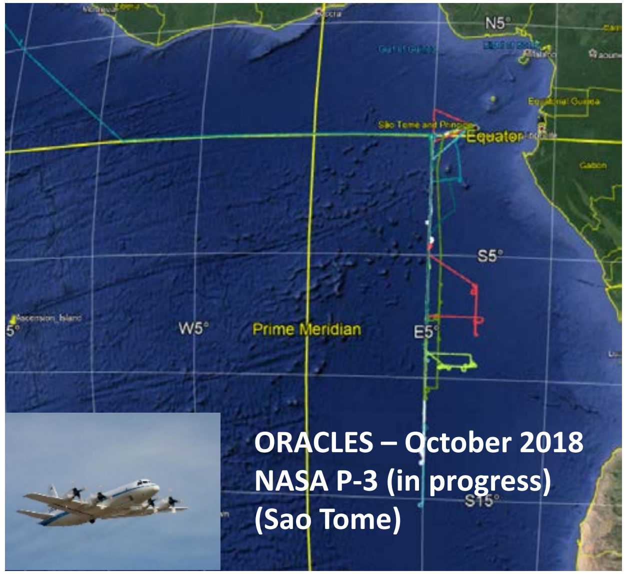
- **NASA EV-S Mission** - Observations of Aerosols above Clouds and their Interactions (ORACLES)
- **Objective** - study the impact of African biomass burning aerosol on cloud properties and the radiation balance over the South Atlantic Ocean.
- **Method** - Airborne deployments of remote sensing and in situ instruments during 2016, 2017, 2018



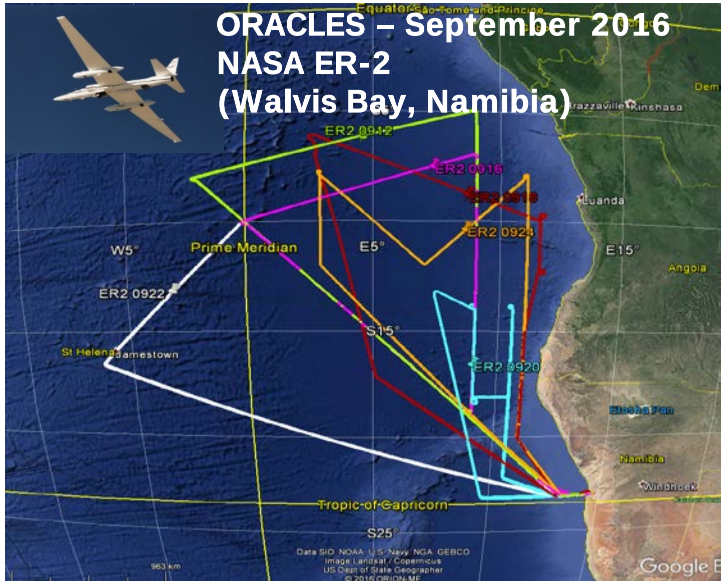


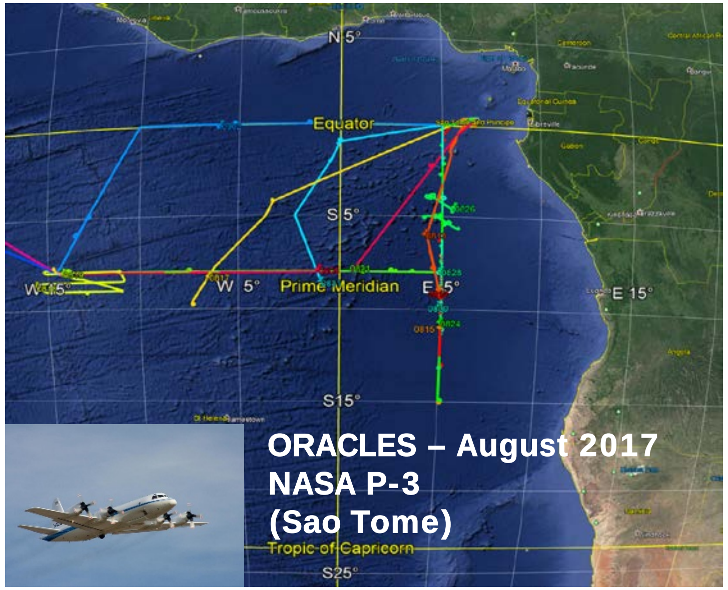
- NASA ER-2 (2016) and P-3 aircraft (2016, 2017, 2018) deployed
- Airborne HSRL-2 lidar deployed from ER-2 (2016) and P-3 (2017, 2018)





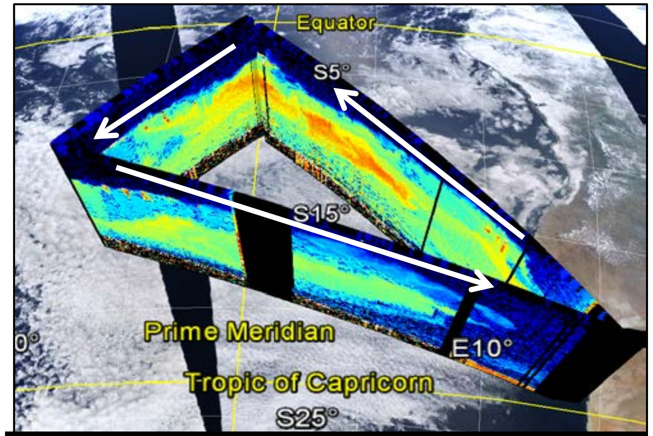
Airborne NASA LaRC HSRL-2 Provides Valuable Aerosol Measurements during NASA ORACLES Mission



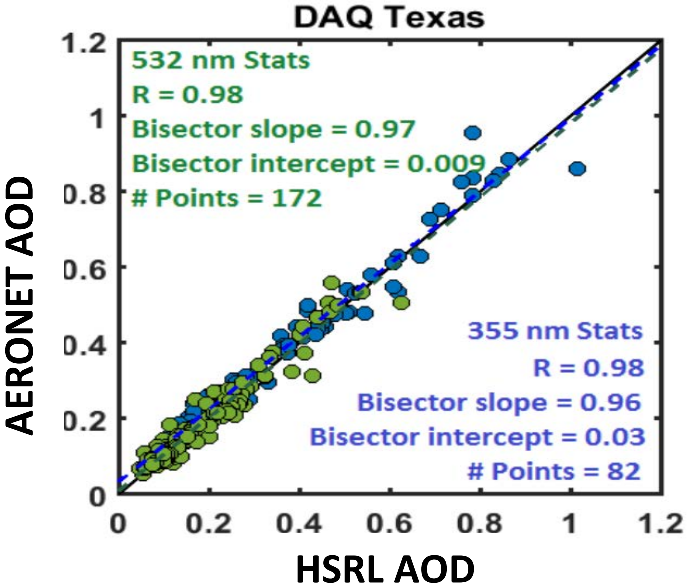


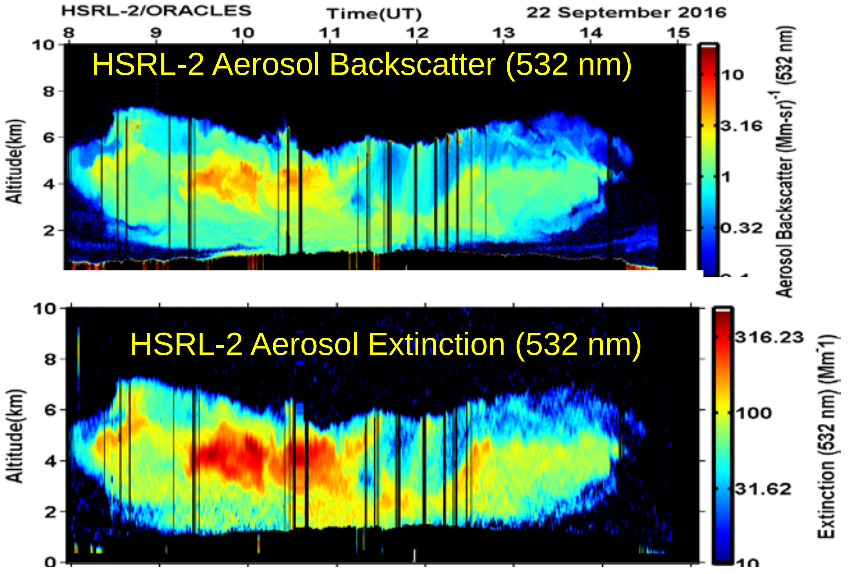
HSRL-2 Data/Measurements/Retrievals:

- Aerosol backscatter, depolarization (355, 532, 1064 nm)
- Aerosol extinction and AOD profiles (355, 532 nm)
- Qualitative aerosol classification
- Mixed layer height
- Multiwavelength aerosol retrievals of particle properties (e.g. effective radius, concentration)

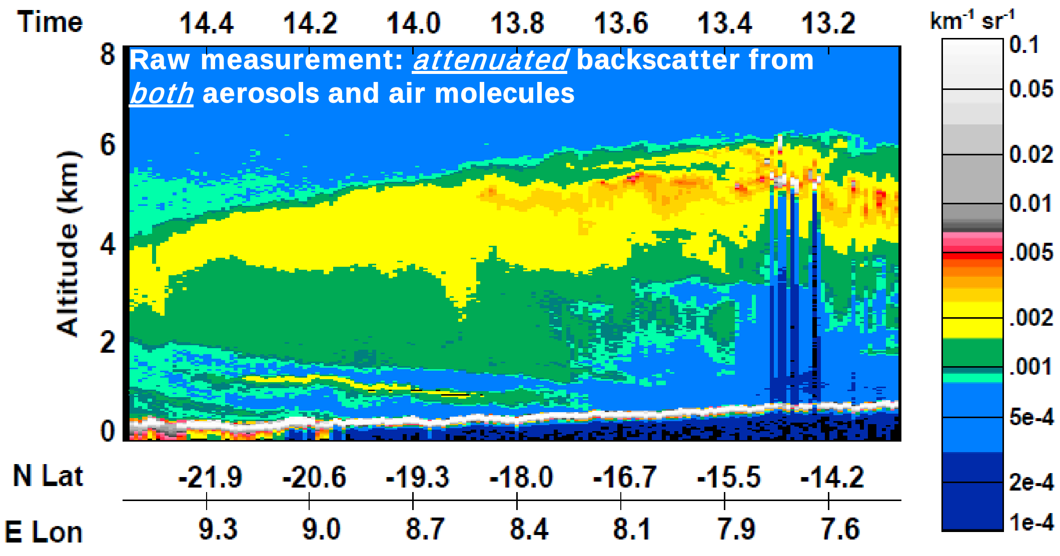


HSRL-2 Aerosol Backscatter Measurements on Sept. 22, 2016





Advanced technique (HSRL) provides greater accuracy for measuring aerosol properties



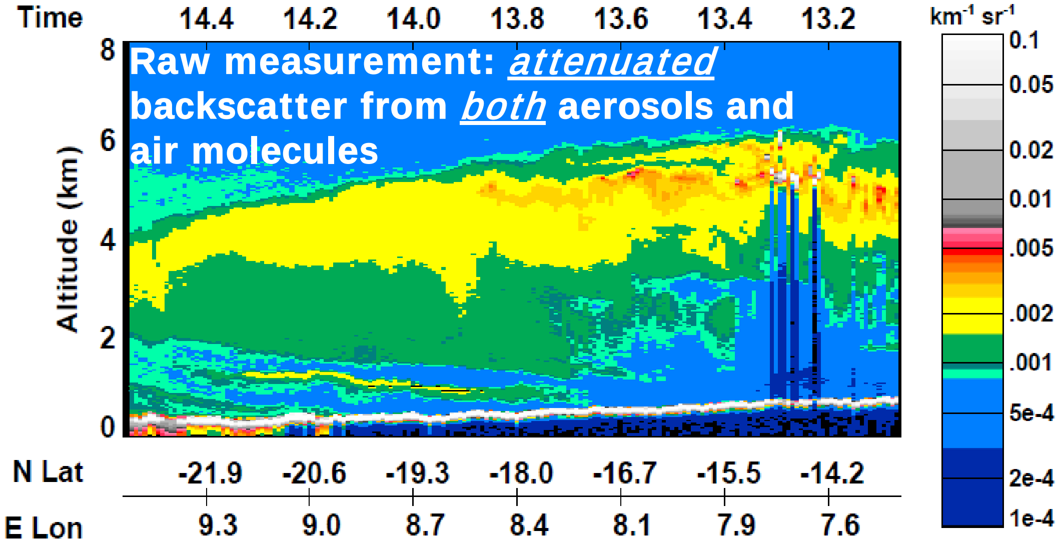
- **Problem:**
  - CALIPSO measures the *attenuated* backscatter coefficient
  - What we actually want is
    - The *true* aerosol backscatter coefficient
    - And the aerosol extinction coefficient
  - To get these, we must somehow correct for extinction as the retrieval proceeds downward through the profile
    - This correction can have significant (30-100%) errors

2 unknowns

$$P_a(r) = \frac{C}{r^2}[\beta_m(r) + \beta_a(r)]\exp\left\{-2\int_0^x [\alpha_m(r') + \alpha_a(r')]dr'\right\}$$

attenuated backscatter

Advanced technique (HSRL) provides greater accuracy for measuring aerosol properties



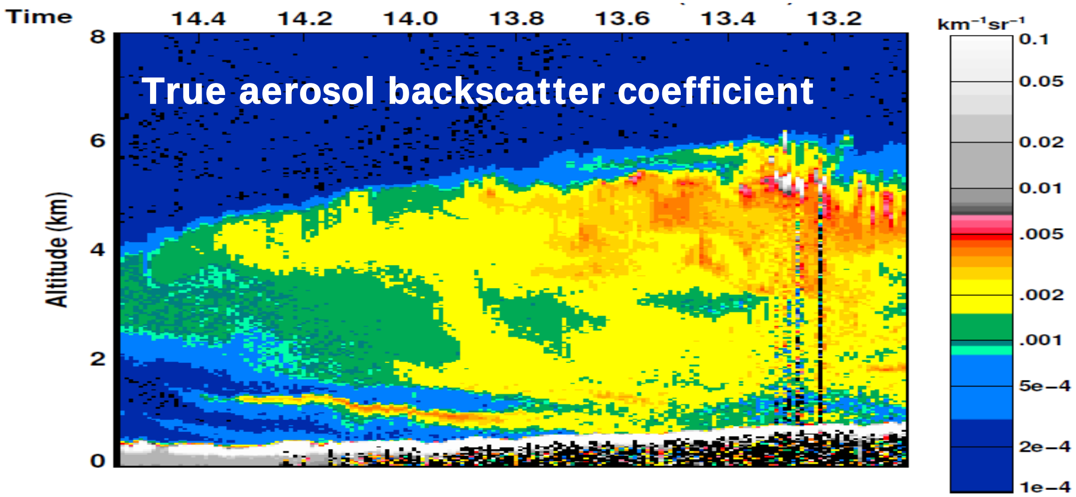
- **Solution:**
  - High Spectral Resolution Lidar (HSRL) measures both total and molecular scattering
  - Provides:
    - True, calibrated aerosol backscatter
    - Aerosol extinction (without assumptions)

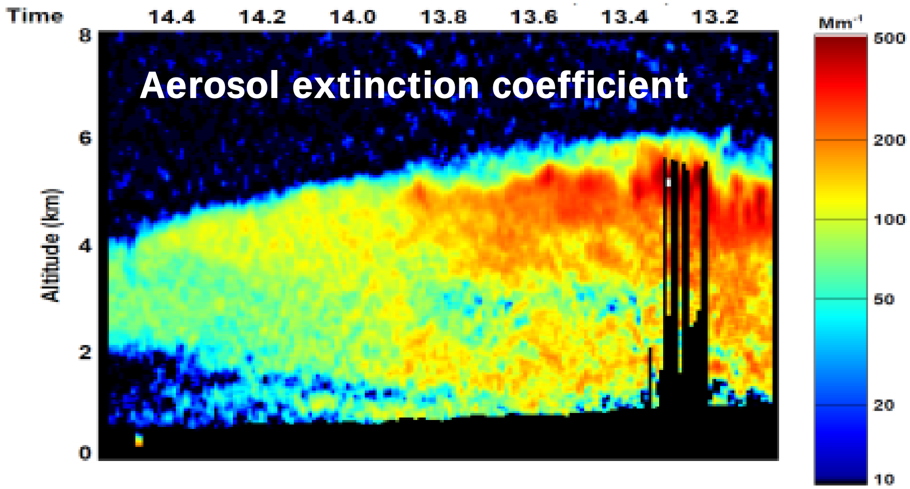
2 unknowns

$$P_a(r) = \frac{C}{r^2}\left[\beta_m(r) + \beta_a(r)\right]\exp\left\{-2\int_0^x \left[\alpha_m(r') + \alpha_a(r')\right]dr'\right\}$$

$$P_m(r) = \frac{C}{r^2}\left[\beta_m(r)\right]\exp\left\{-2\int_0^x \left[\alpha_m(r') + \alpha_a(r')\right]dr'\right\}$$

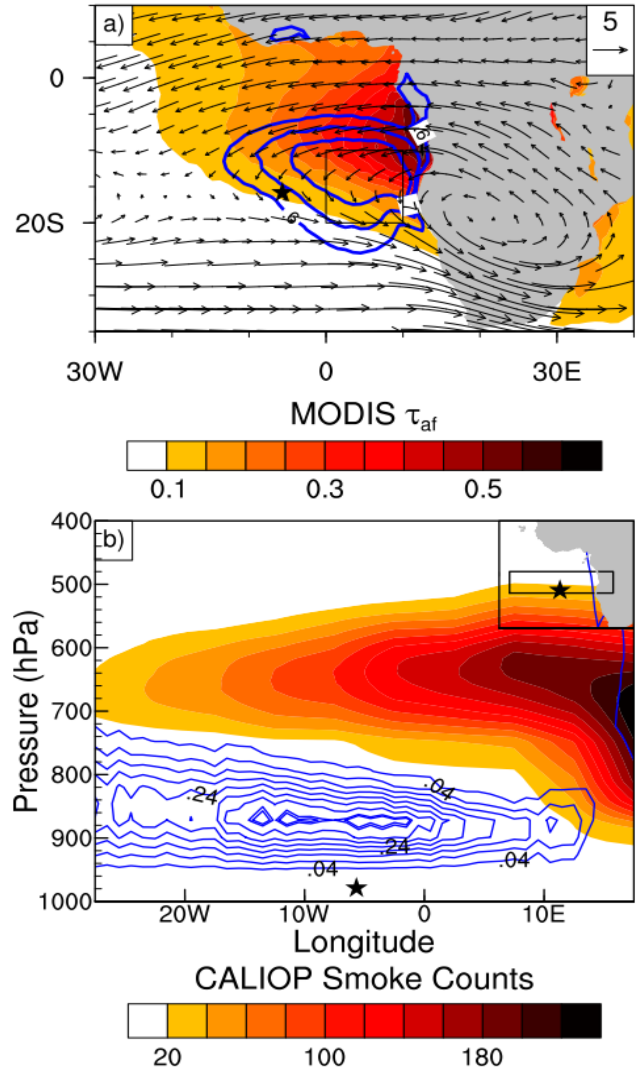
- **Solution: High Spectral Resolution Lidar**



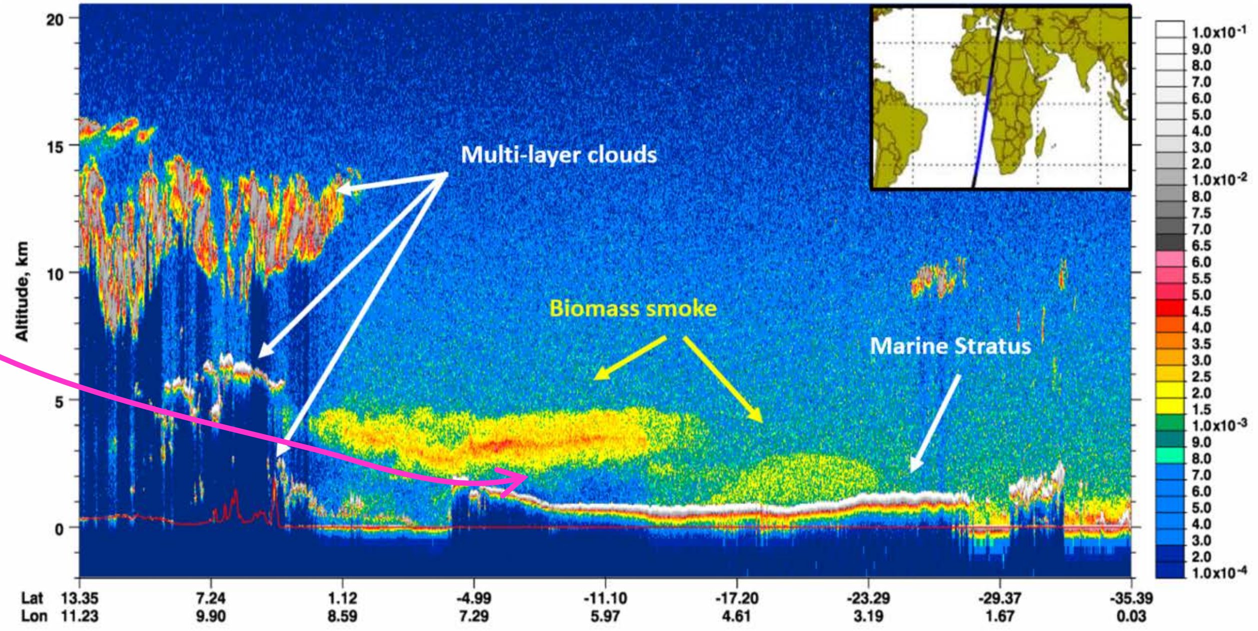


CALIOP (on CALIPSO) Measurements of Smoke above Clouds

- CALIOP operational aerosol profiles used to determine proximity of elevated smoke layers to underlying clouds
- Problem: CALIOP V4 532 nm aerosol layer detection often misses lower boundary of thick smoke layer due to strong attenuation of upper part of smoke layer (current V4 algorithm CALIOP 1064 nm penetrates further but uses 532 nm layer boundaries) resulting in:
  - Underestimate of above cloud AOD (ACAOD)
  - Overestimate in the size of the gap between smoke and cloud



Adebiyi et al., 2015



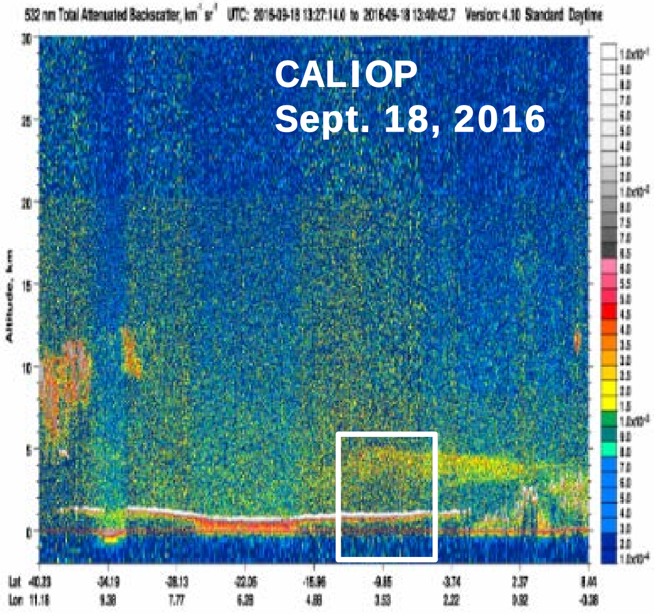
Evaluation of CALIOP Above Cloud AOD (ACAOD) Using HSRL-2

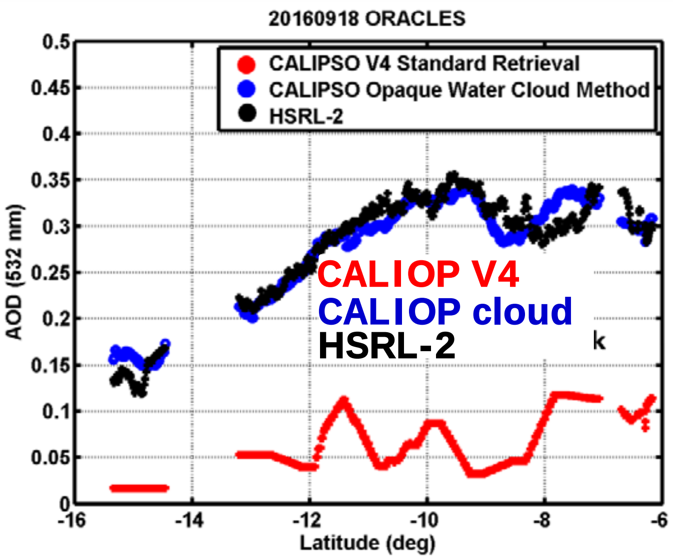
1. V4 Operational product
   - layer detection scheme
   - extinction retrieval algorithm
   - inferred lidar ratio
2. Opaque water cloud ("Depolarization Ratio Method" – Hu et al., GRL, 2007)
   - Layer-integrated attenuated backscatter and depolarization of clouds
   - Assumed cloud lidar ratio (18.9 sr)

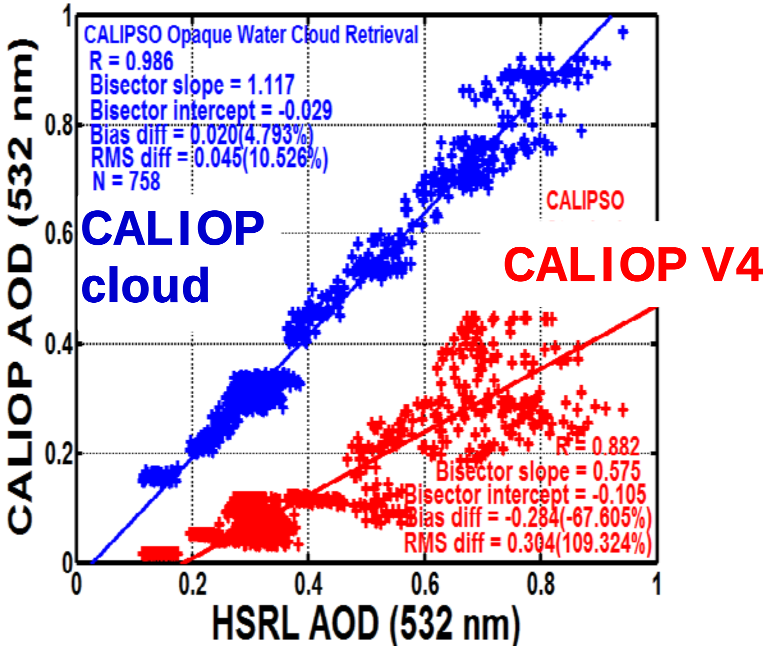
optical depth of aerosol layer (τ_{top}); layer-integrated attenuated backscatter of water cloud (γ'_{water})

$$\tau_{top} = -\frac{1}{2}\ln\left(2S_c\gamma'_{water}\left(\frac{1-\delta}{1+\delta}\right)^2\right)$$

cloud lidar ratio (~18.9 sr) (S_c); depolarization ratio of cloud (δ)



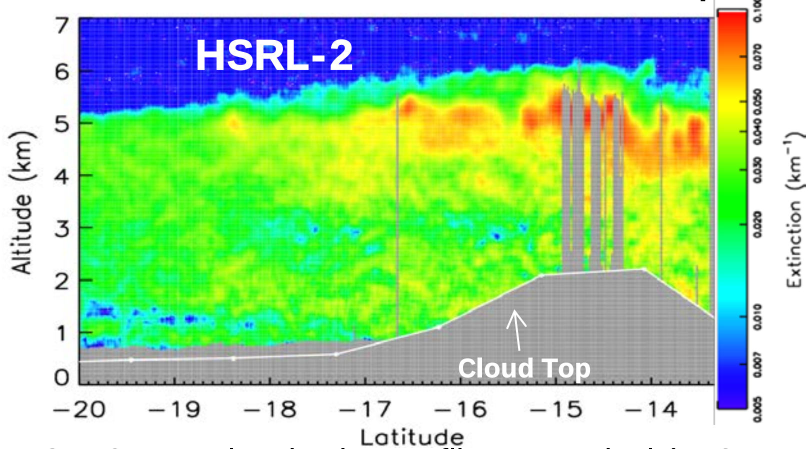




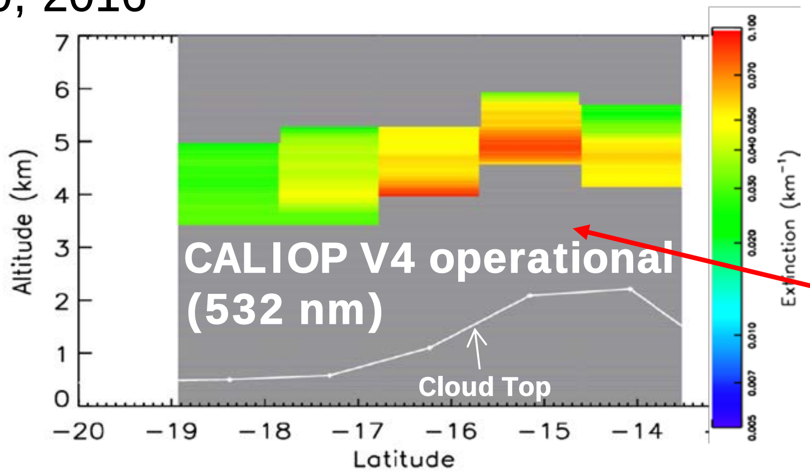
- ➢ **CALIOP V4 operational retrievals miss much of the ACAOD**
- ➢ **CALIOP ACAOD from opaque water cloud method agrees well with the HSRL-2 ACAOD**

Evaluation of CALIOP Aerosol Extinction Profiles derived using CALIOP ACAOD Constraint

Sept. 20, 2016



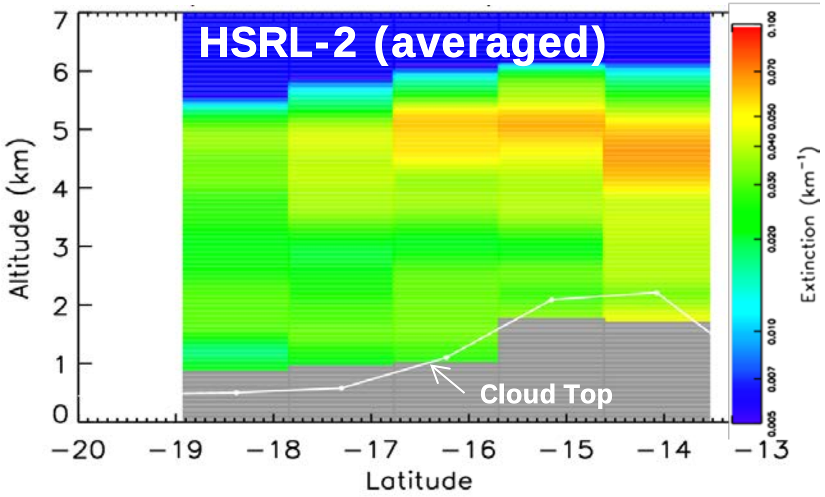
HSRL-2 aerosol extinction profiles at nominal (~13 km horizontal, 315 m vertical) resolution



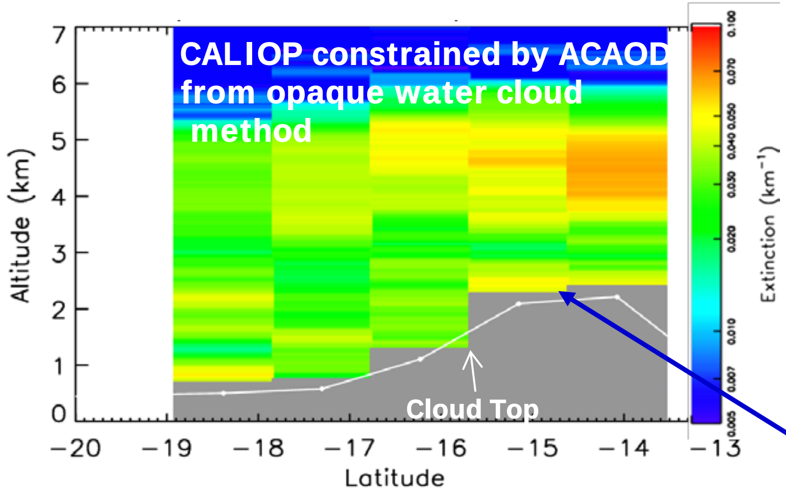
CALIOP V4 Operational aerosol extinction profiles (532 nm)

CALIOP V4 Operational aerosol extinction profiles

- **Match HSRL-2 extinction profiles well at the top of the smoke layer**
- **Miss a significant amount of aerosol extinction in the lower part of the layer**



HSRL-2 aerosol extinction profiles averaged to 120 km, 330 m vertical resolution

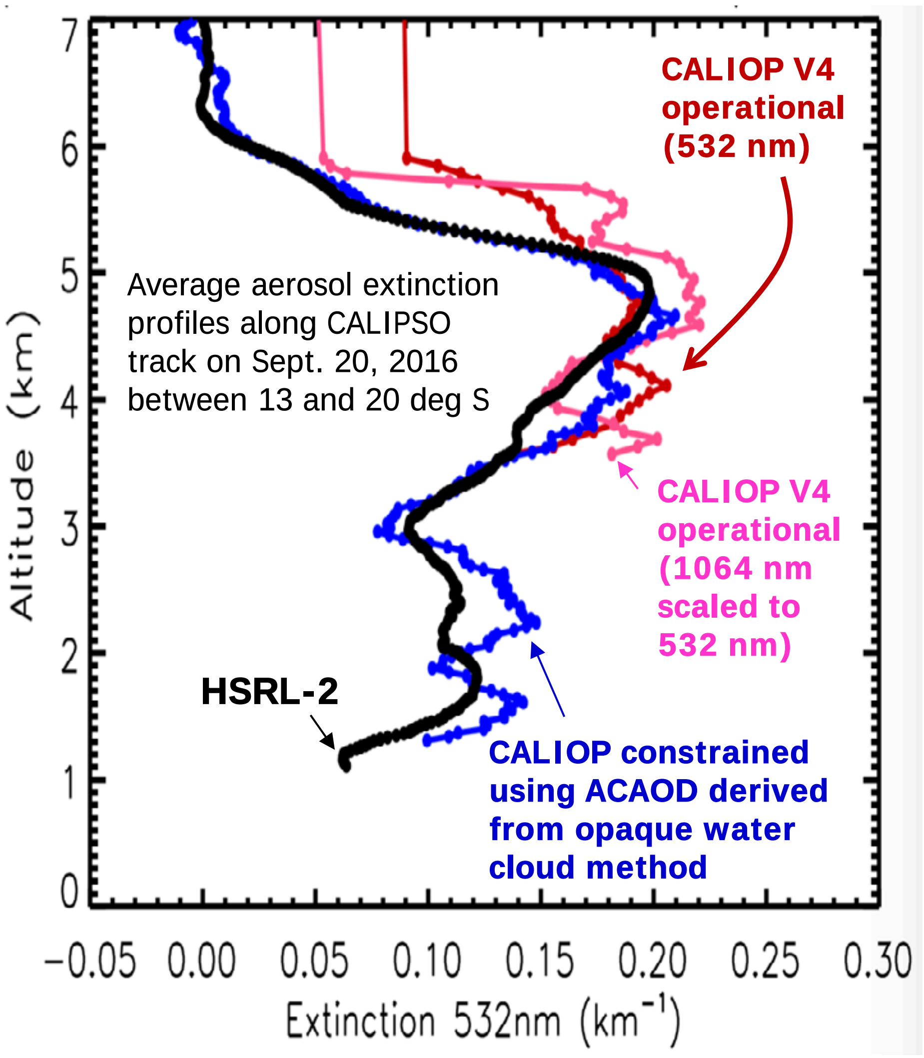


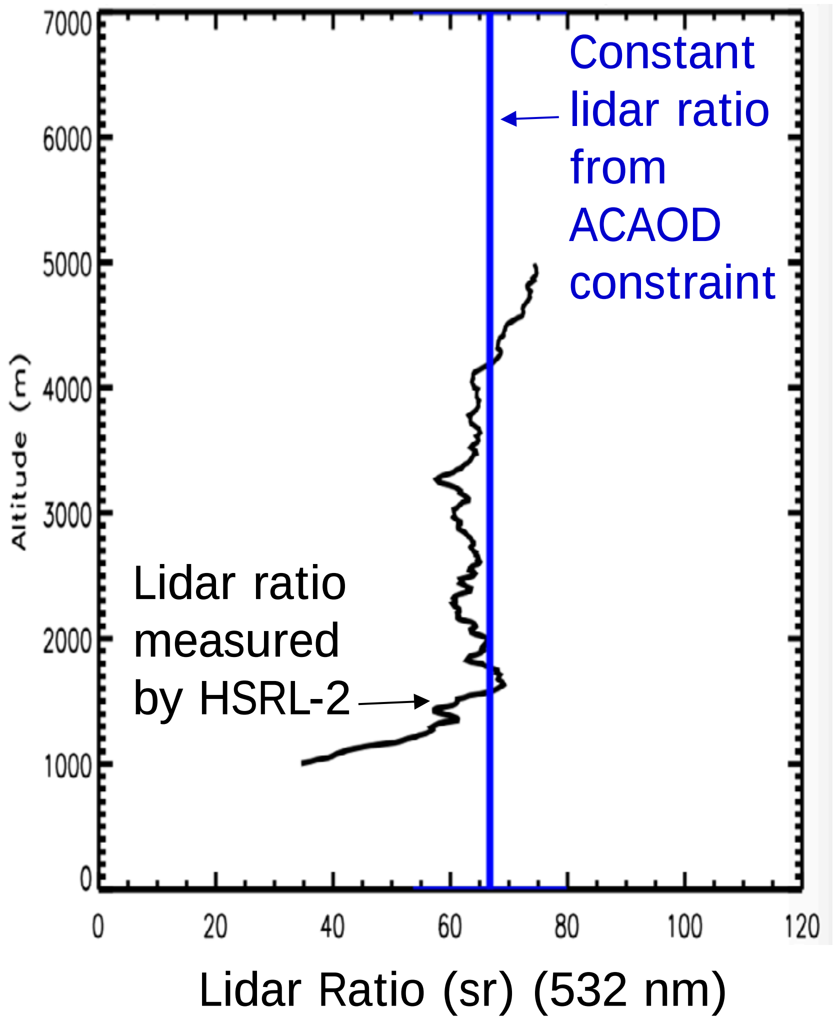
CALIOP aerosol extinction profiles derived using the CALIOP ACAOD constraint obtained from the opaque water cloud ("depolarization ratio") method.

CALIOP aerosol extinction profiles derived by using the ACAOD computed from the CALIOP opaque water cloud method as a constraint

- **Much better agreement with HSRL-2**
- **Extend farther and much closer to underlying cloud**

Caution! Aerosol extinction retrievals using ACAOD as a constraint assume aerosol properties (i.e. lidar ratio) are constant

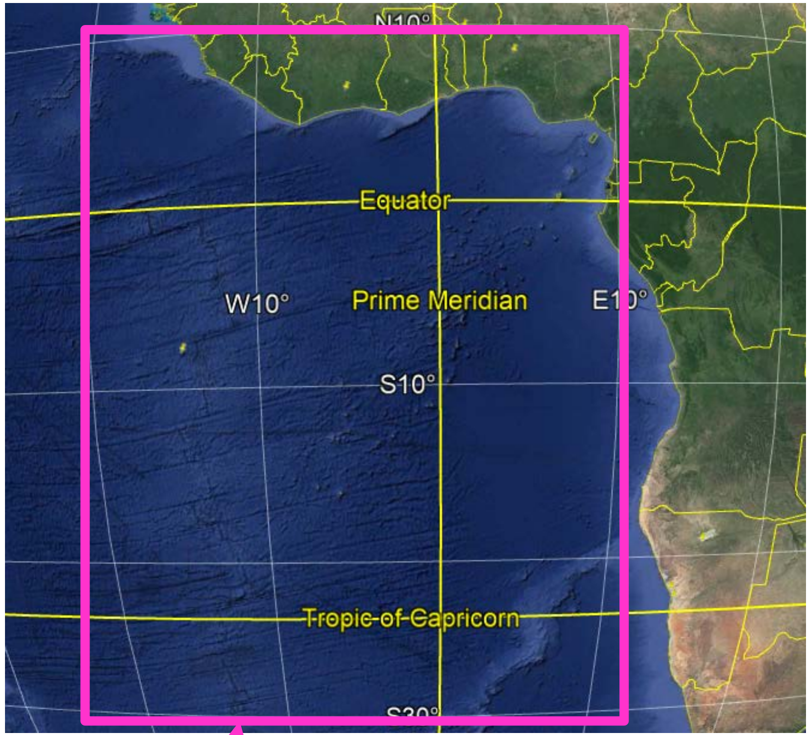




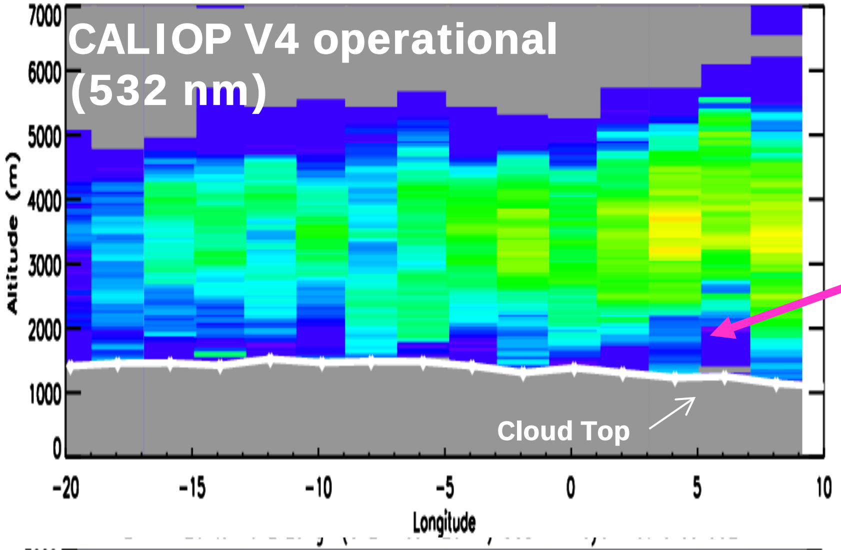
Profiles derived using the ACAOD constraint obtained from the CALIOP opaque water cloud method assume a constant mean lidar ratio over the aerosol layer

- On average, for this Sept. 20 case of smoke over clouds this assumption is OK
- For other cases, or shorter periods during this case, this is not a good assumption ...we'll show this later

Meridionally averaged aerosol extinction profiles computed using CALIOP ACAOD constraint

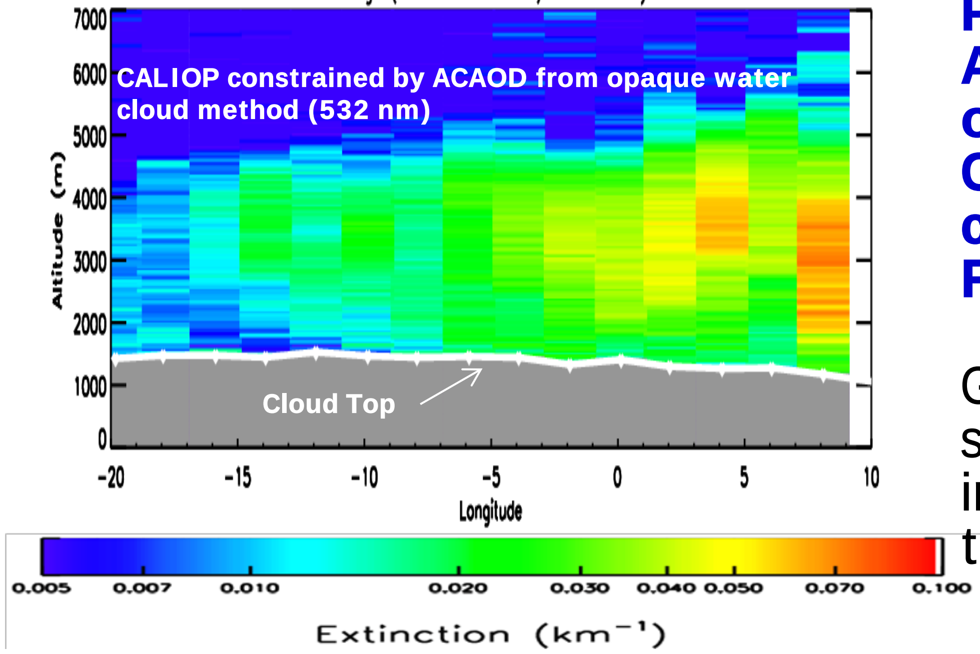


Meridionally averaged aerosol extinction profiles were computed for the SE Atlantic Ocean region (30 S to 10 N) during Jul-Oct 2015-2016. These use both daytime and nighttime CALIOP measurements.



CALIOP V4 operational algorithm (532 nm).

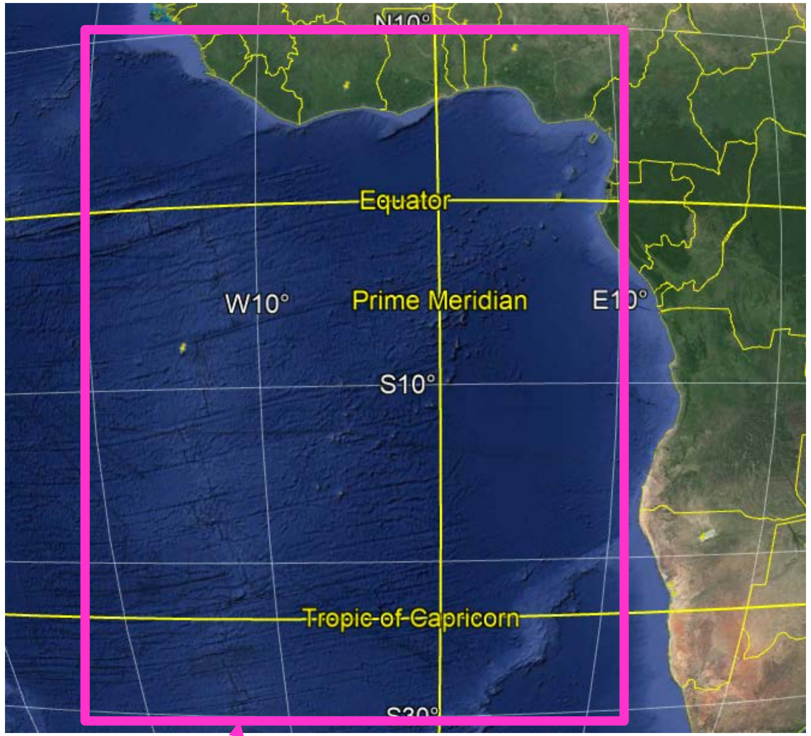
Note the gap between the cloud top and the bulk of the smoke layer.



Profiles derived using the ACAOD constraint obtained from the CALIOP opaque water cloud ("Depolarization Ratio – DR") method.

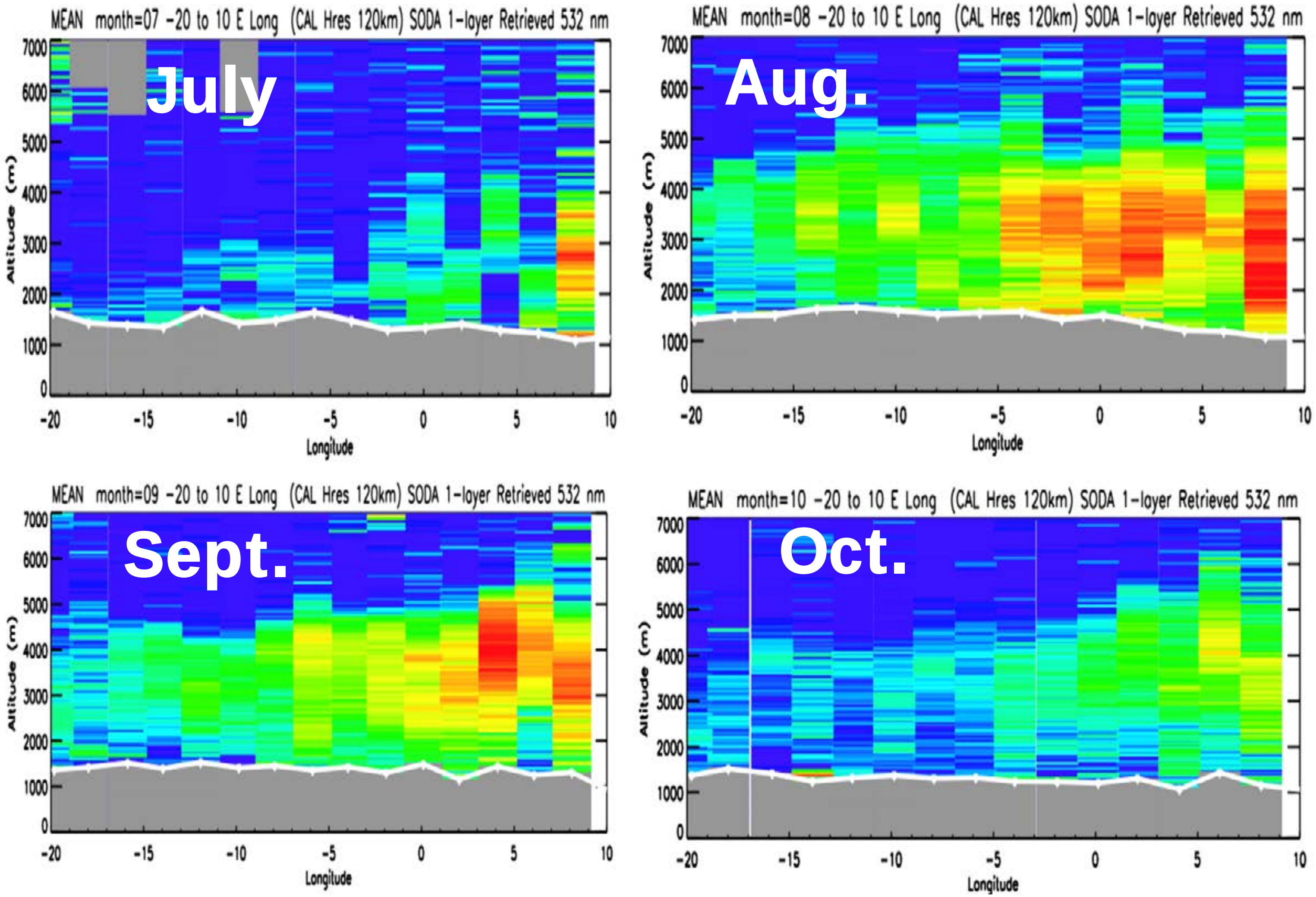
Gap has significantly reduced so that smoke and clouds are in close proximity most of the time.

Meridionally averaged aerosol extinction profiles computed using CALIOP ACAOD constraint – variability with month

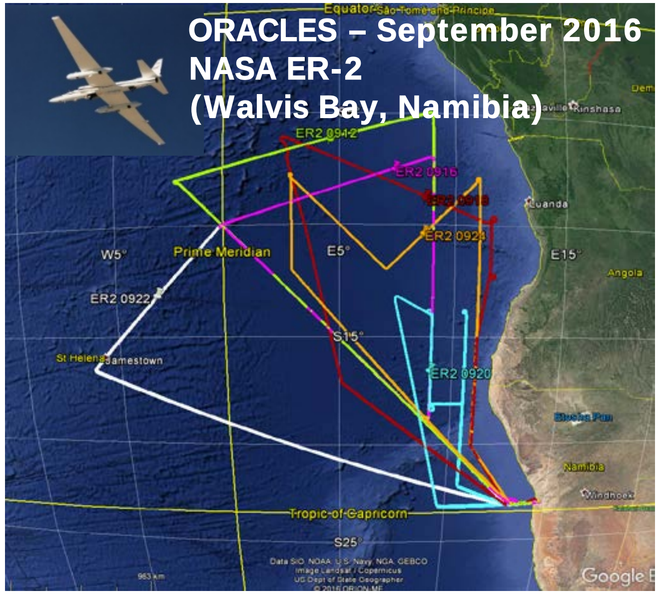


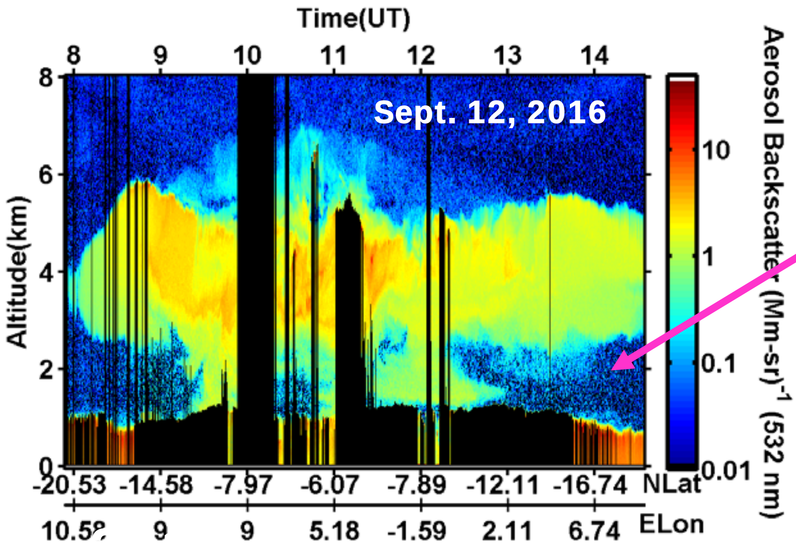
Meridionally averaged aerosol extinction profiles were computed for the SE Atlantic Ocean region (30 S to 10 N) during 2015-2016. These use both daytime and nighttime CALIOP measurements.

Gap between smoke and clouds varies with month

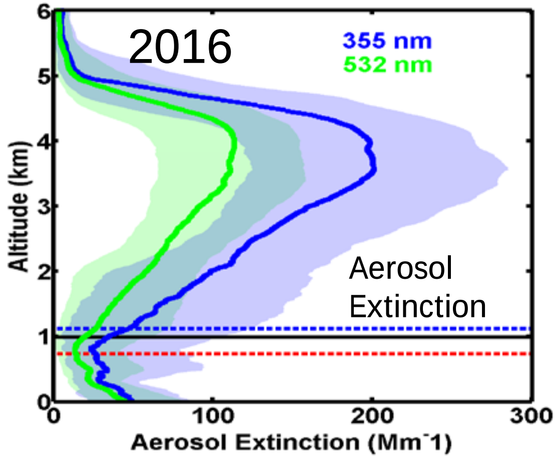


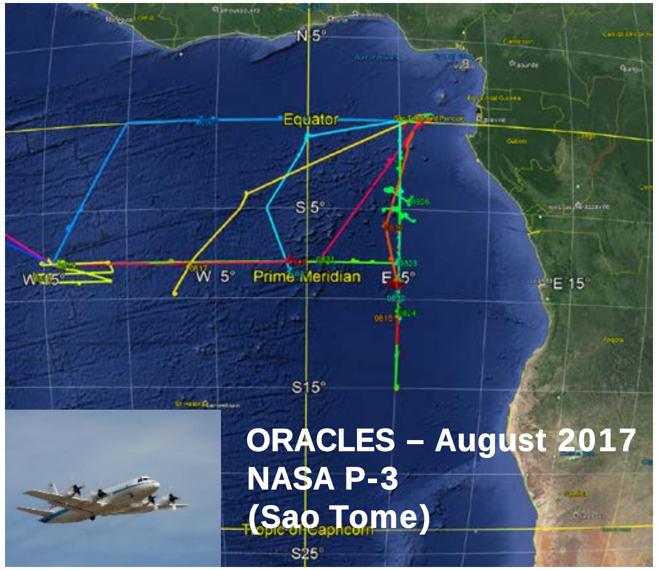
Comparison of aerosol distributions measured by HSRL-2 between 2016 and 2017

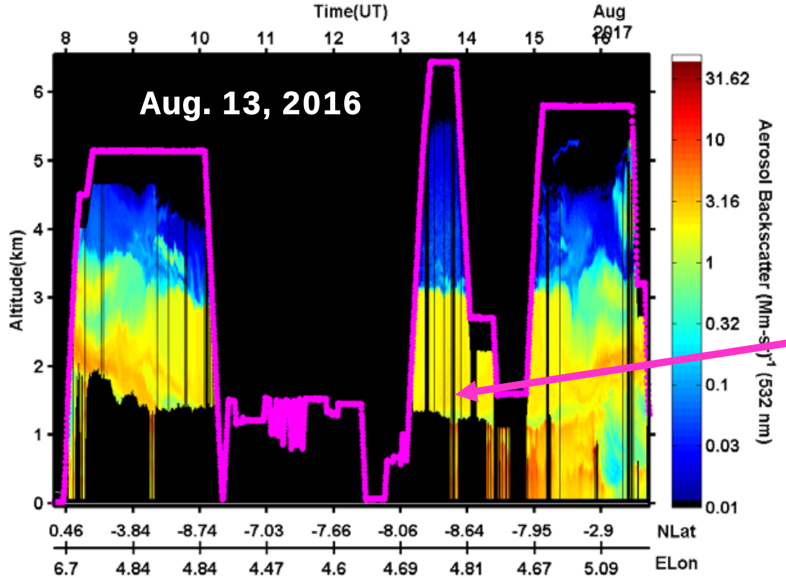




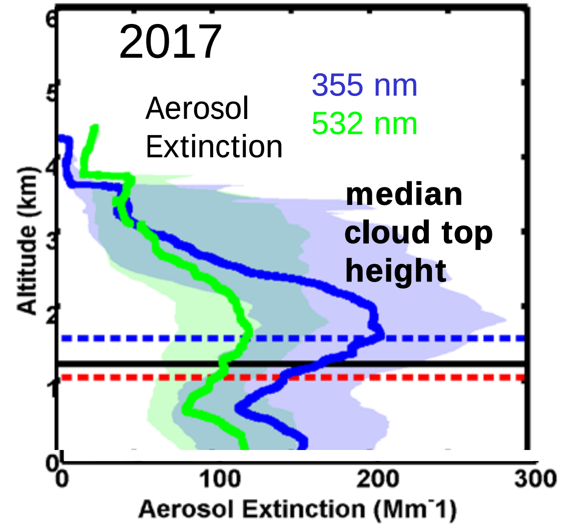
During ORACLES 2016, there was often a gap (or clean layer) observed between bottom of elevated aerosol layer and the underlying low cloud layer



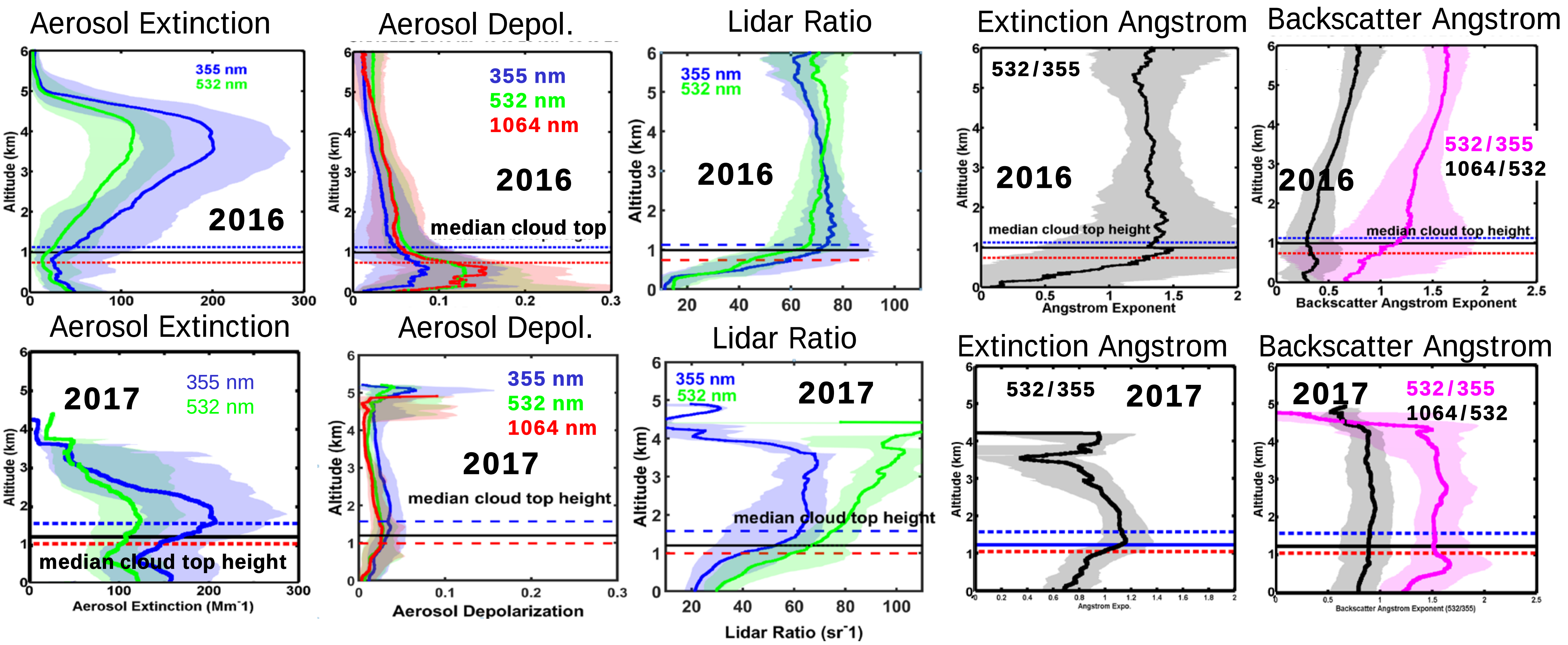




During ORACLES 2017, there was rarely a gap (or clean layer) observed between bottom of elevated aerosol layer and the underlying low cloud layer



Comparison of observed aerosol variables measured by HSRL-2 between 2016 vs. 2017



- Size (extinction Angstrom exponent), shape (aerosol depolarization) and composition (lidar ratio)
- Less depolarization in 2017 because less dust
- Differences in lidar ratio, particularly 532 nm lidar ratio in upper part of plume

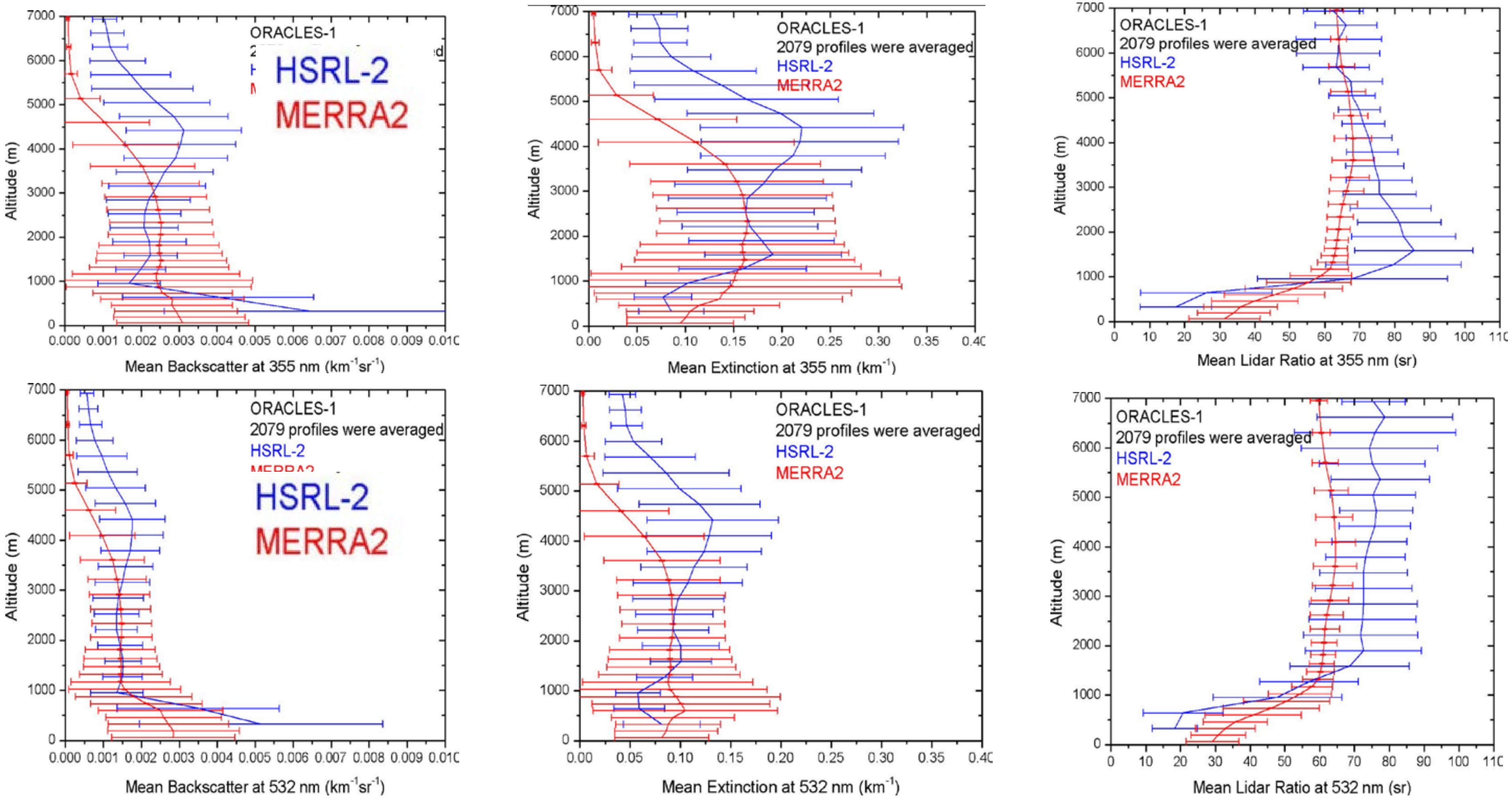
HSRL-2 and GEOS-5 MERRA-2 Comparison along ER-2 tracks during ORACLES-2016

- MERRA-2 underestimates height of top of smoke layer
- MERRA-2 underestimates lidar ratios

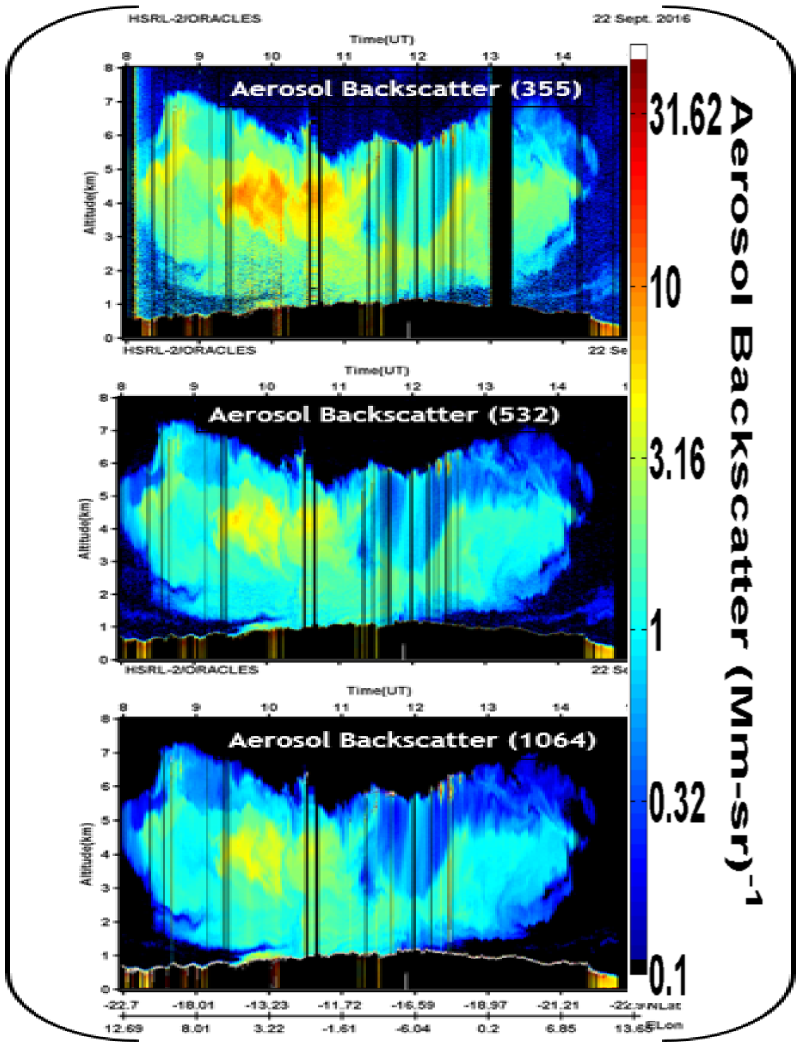
Aerosol Backscatter | Aerosol Extinction | Aerosol Lidar Ratio

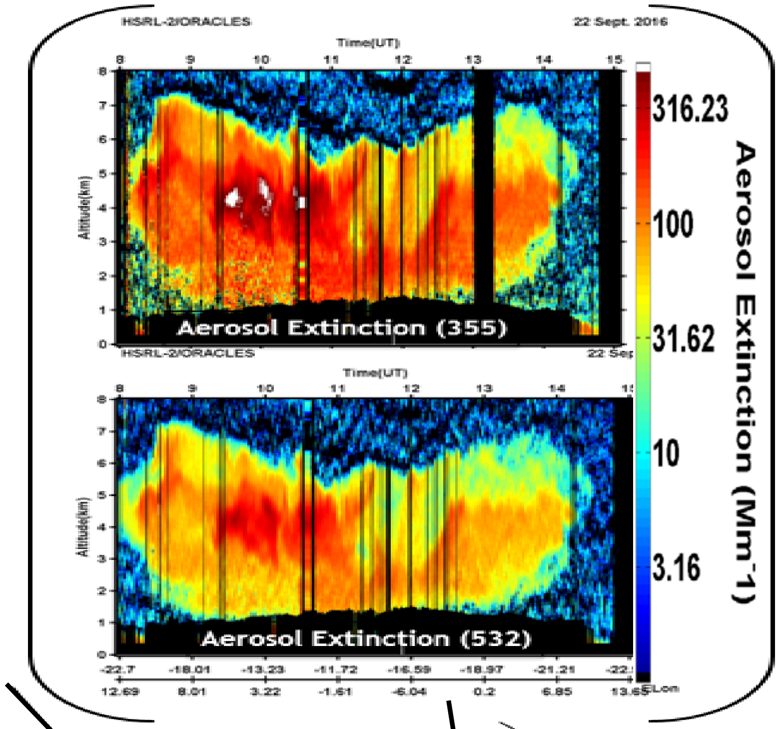
355 nm

532 nm



Multiwavelength HSRL-2 retrievals characterize aerosol concentration and size during ORACLES





Aerosol Backscatter:
355 nm
532 nm
1064 nm

+

Aerosol Extinction:
355 nm
532 nm

Input

Multiwavelength lidar retrieval algorithms (Müller et al, 1999; Veselovskii et al. 2002; etc)

lidar measurements

particle size distribution

INVERSION

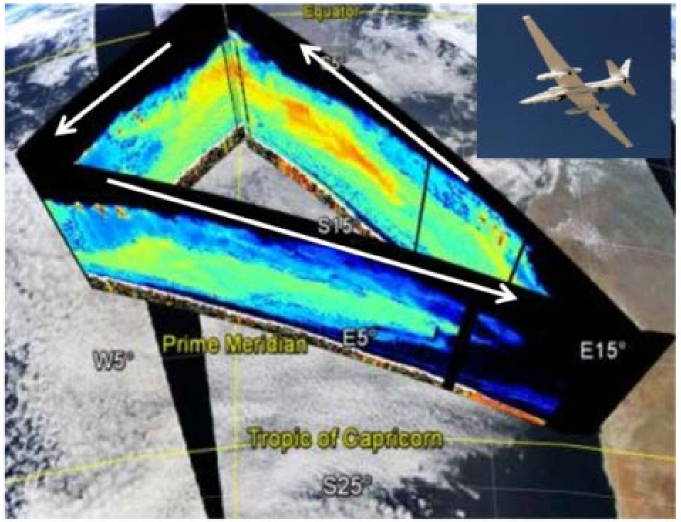
$$\beta(\lambda) = \int K_{\beta}(r, m, \lambda) v(r) dr$$

$$\alpha(\lambda) = \int K_{\alpha}(r, m, \lambda) v(r) dr$$

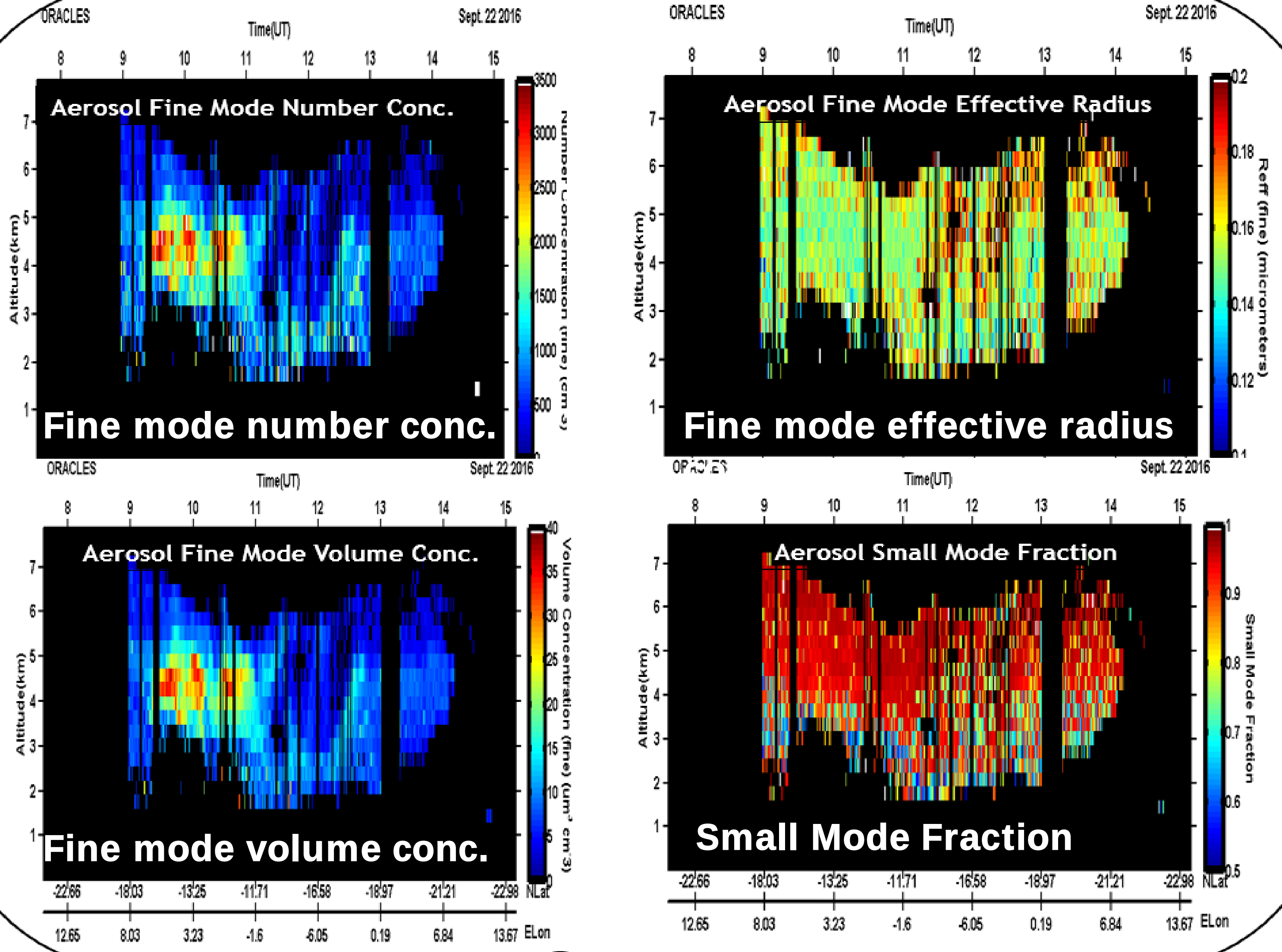
size, refractive index, wavelength

3β+2α (i.e. 3 backscatter + 2 extinction) considered the minimum information content necessary for microphysical retrievals (*Bockmann et al*, 2005)

Multiwavelength HSRL-2 retrievals characterize aerosol concentration and size during ORACLES

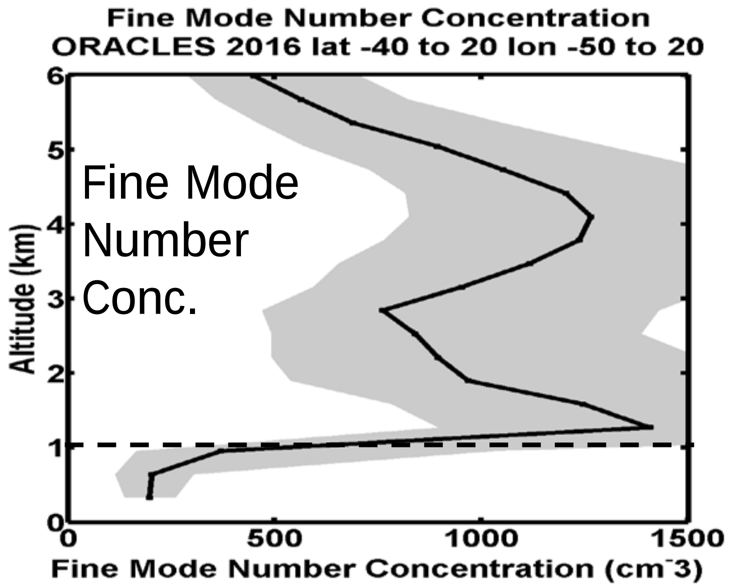


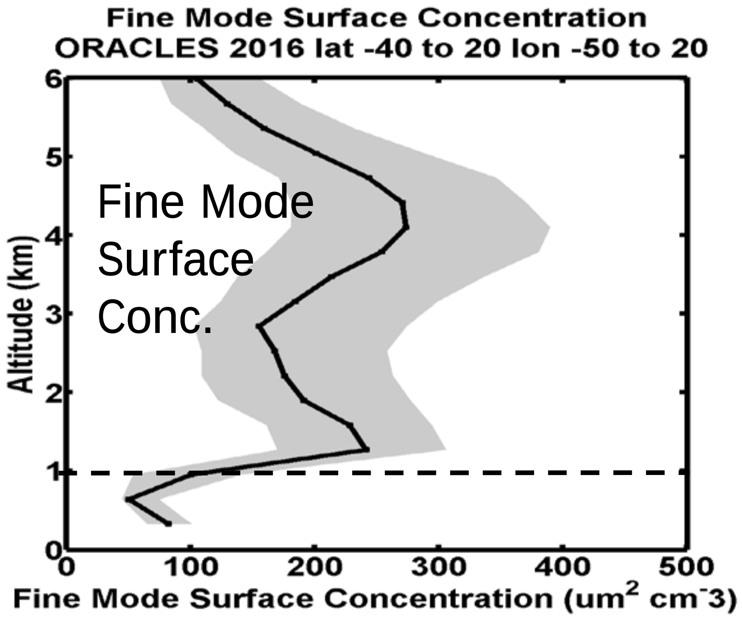
- Microphysical parameters retrieved and archived:
  - Concentration (fine and total) (number, surface, volume)
  - Effective radius (fine and total)
  - Small mode fraction

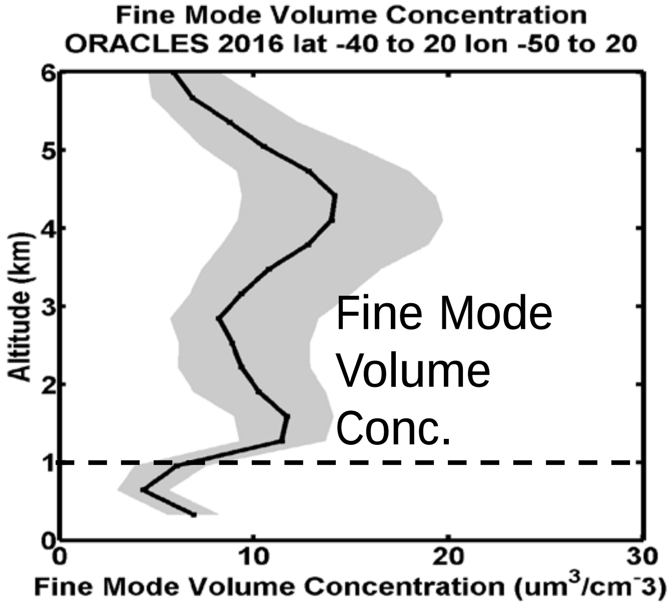


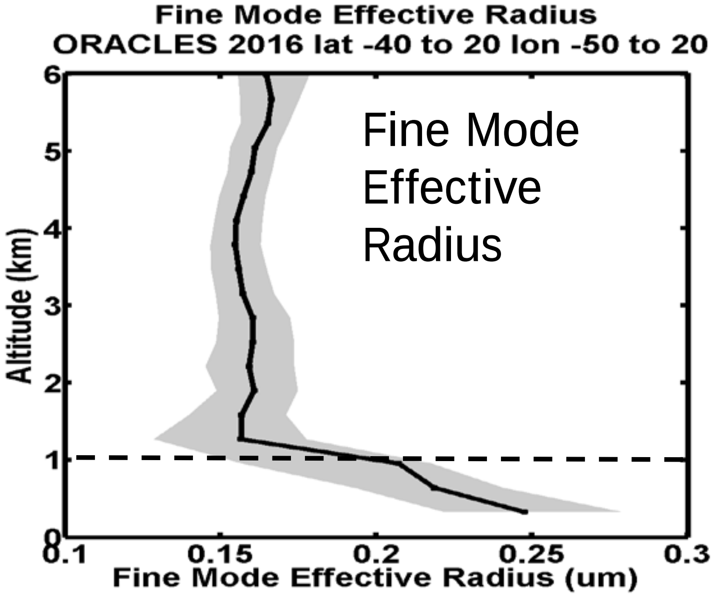
Output

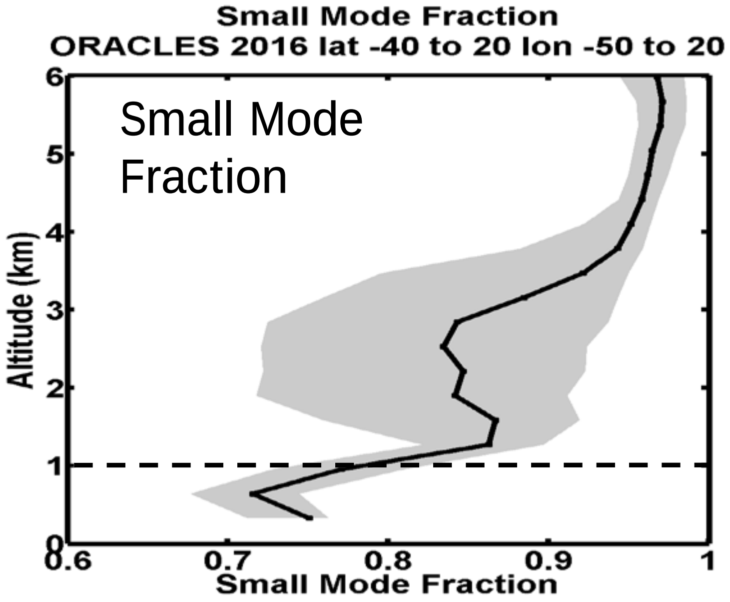
Median Profiles of Aerosol Properties during ORACLES-2016 from HSRL-2





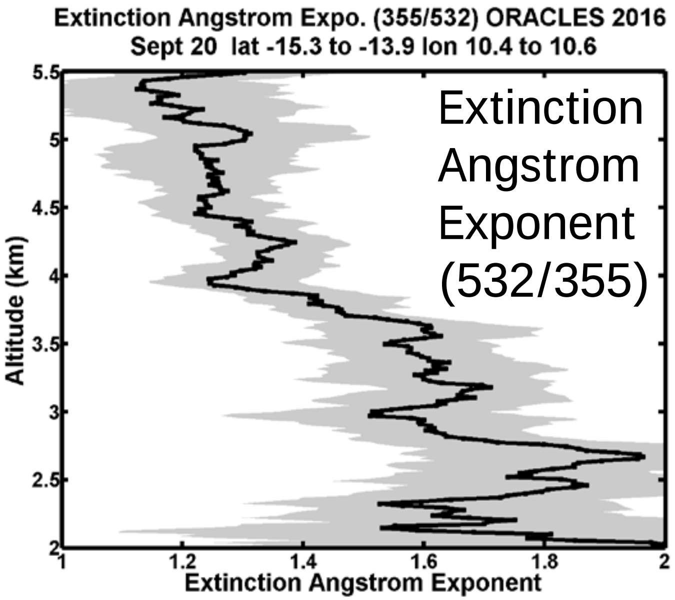


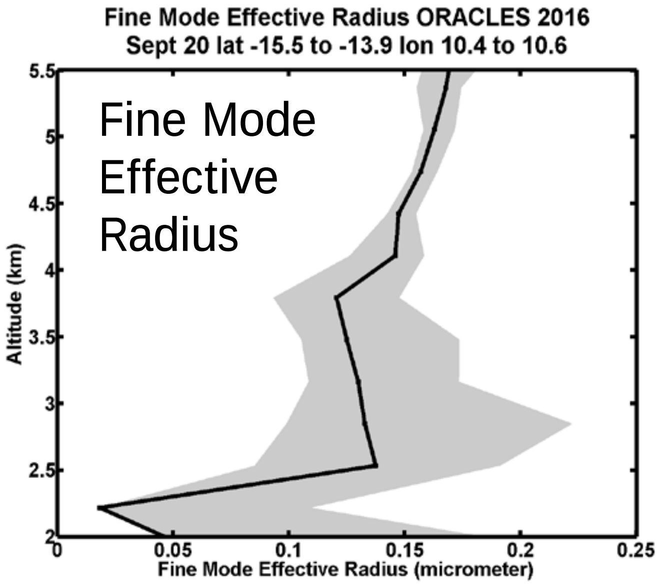


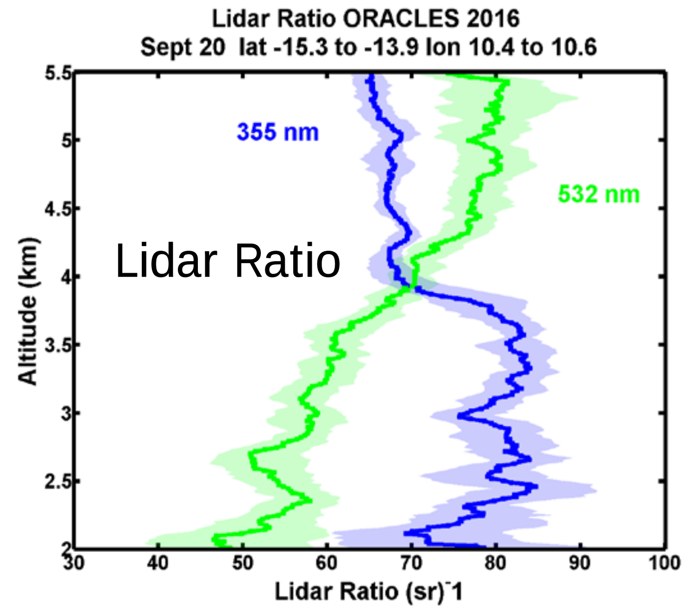


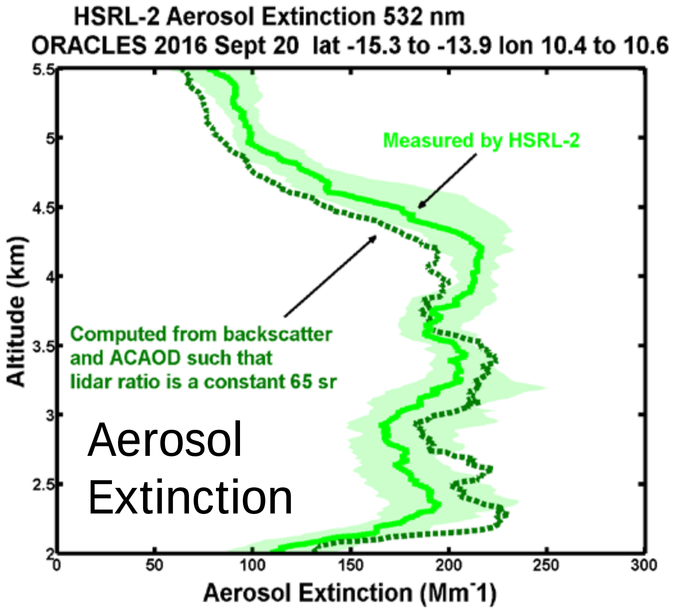
- Significant change in Small Mode Fraction in aerosol layer
- Large change in aerosol properties above vs. below cloud

Vertical Variability of Smoke Properties Observed by HSRL-2

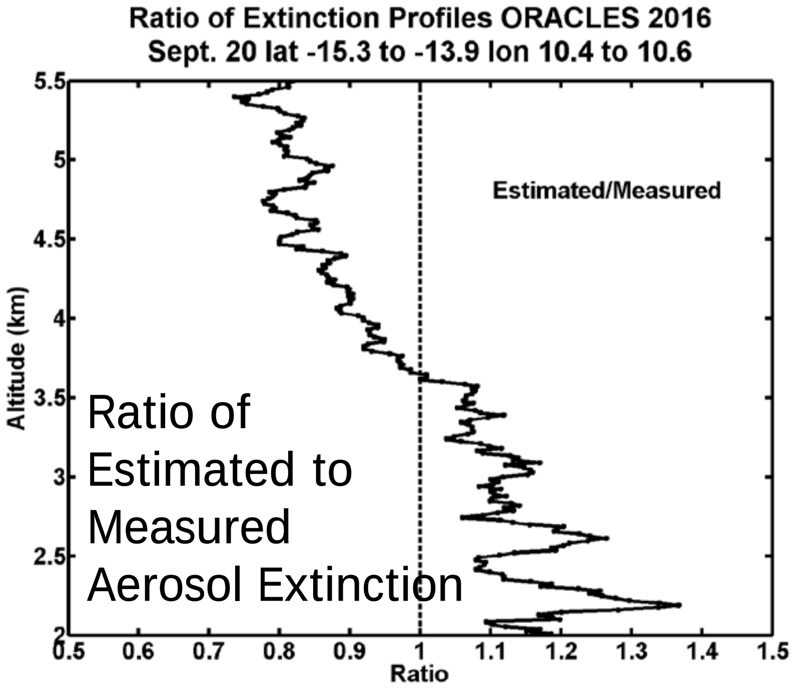








- Example of vertical variability of smoke properties (Burton et al., 2018, Appl. Optics)
- Increase in fine mode effective radius leads to increase in lidar ratio (532 nm)
- In this case of single aerosol type (smoke), assuming a constant lidar ratio results in ~20-40% errors in derived aerosol extinction



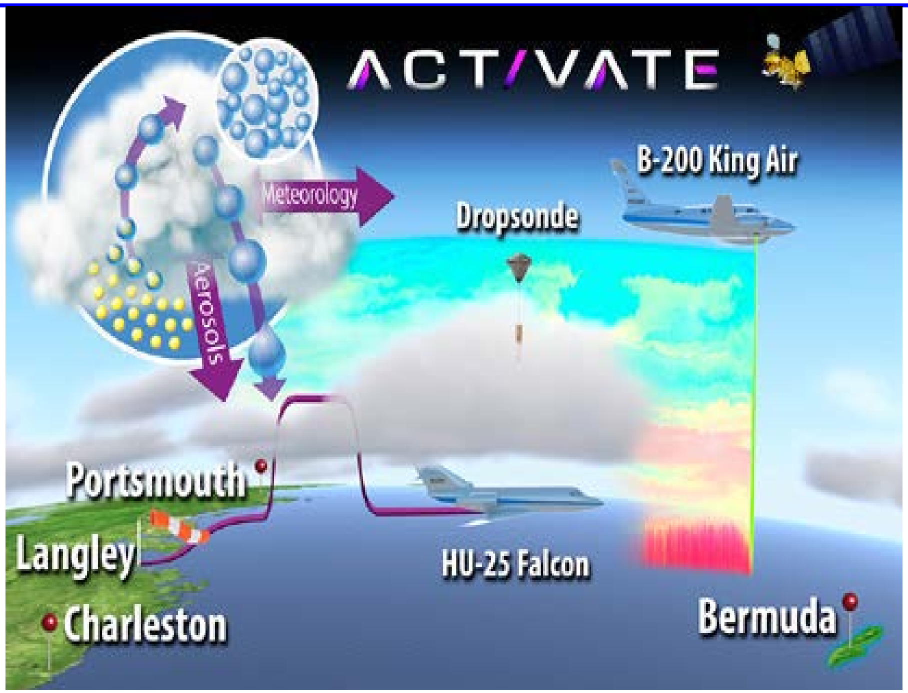
Summary

- Airborne HSRL-2 measured/retrieved smoke layer aerosol optical and microphysical properties during NASA ORACLES missions
- Comparisons of CALIOP V4 operational and HSRL-2 aerosol measurements reveal:
  – CALIOP V4 Above Cloud AOD (ACAOD) is ~60-70% lower than HSRL-2 ACAOD
  – CALIOP V4 aerosol extinction near layer top in good agreement with HSRL-2
  – CALIOP V4 532 nm smoke lidar ratio (70 sr) in good agreement with HSRL-2 measurements of smoke lidar ratio
  – CALIOP V4 aerosol extinction profiles do not resolve well smoke just above cloud top
- Comparisons of CALIOP (DR – opaque cloud method) and HSRL-2 aerosol measurements reveal:
  – CALIOP DR Above Cloud AOD (ACAOD) agrees much better (within 10%) with HSRL-2 ACAOD
  – CALIOP DR aerosol extinction profiles (532 nm) agree much better with HSRL-2 profiles and reveal more smoke near cloud top
- HSRL-2 measurements and retrievals reveal vertical variability in smoke layer optical properties and particle size

Backup

EVS-3 Investigation Summary:

Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment (ACTIVATE)



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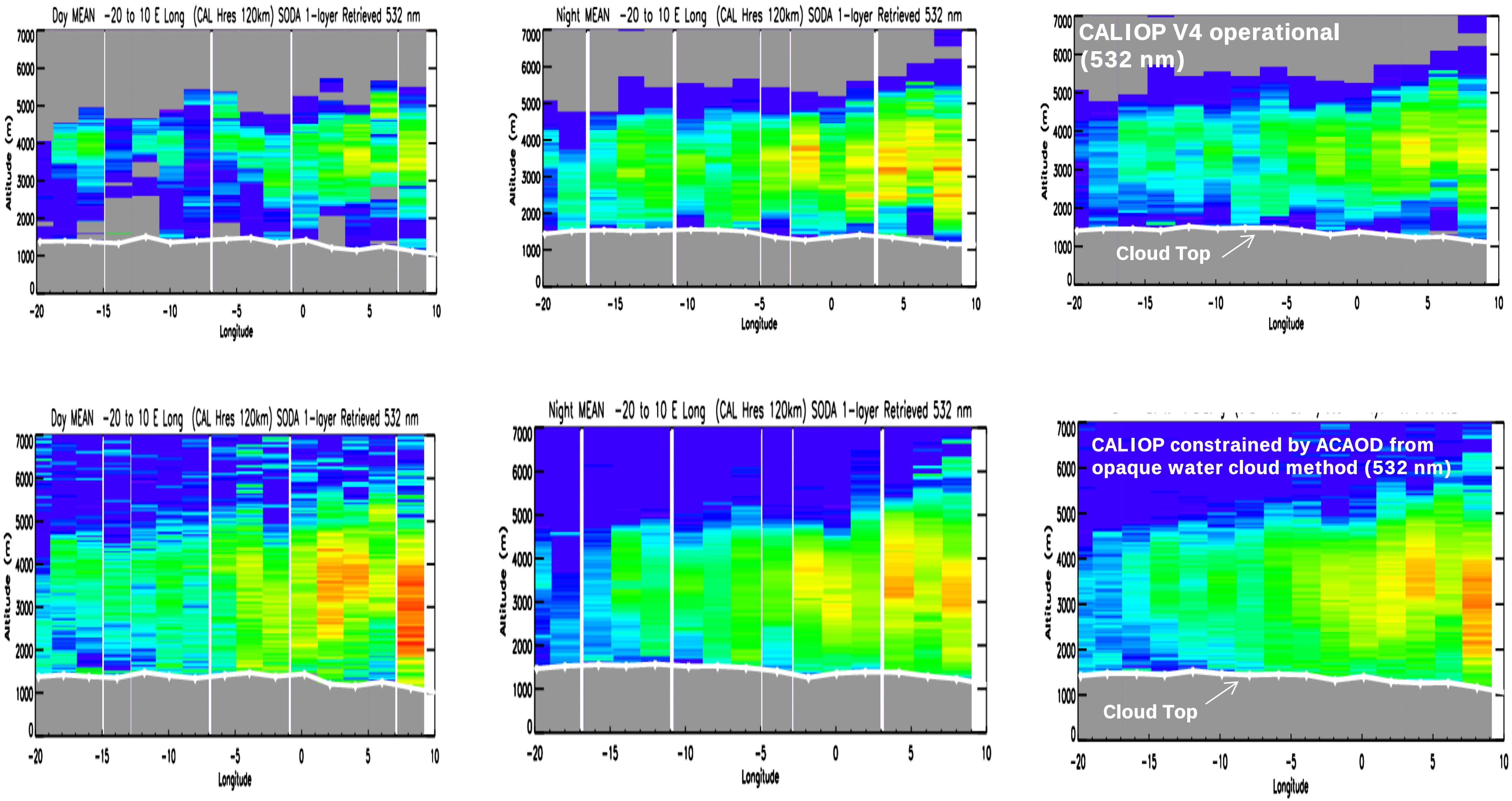
Partnering Institutions: Univ. Arizona, NASA LaRC, NASA GISS, SSAI, NIA, PNNL, BNL, Univ. Miami

Science: Build an **unprecedented dataset** to better understand aerosol-cloud-meteorology interactions, improve physical parameterizations for Earth system and weather forecasting models, assess remote sensing retrieval algorithms, and guide plans for future satellite missions.

- Investigation start date: January 2019
- Airborne element:
  - Platforms: NASA LaRC aircraft (HU-25 Falcon + B-200 King Air)
  - Based out of NASA LaRC, Hampton, VA
- Approach:
  - Measurements: In situ and remote sensing measurements of aerosol and cloud distributions and properties, atmospheric state
  - Modeling: Particle dispersion, chemical transport, single-column, large-eddy simulation, cloud-resolving, weather forecasting and climate modeling
- Deployments:
  - ~**50 joint airplane missions per year** over western North Atlantic Ocean in each of three years (~600 hours and ~150 flights over three years for each airplane)

Meridionally averaged aerosol extinction profiles computed using CALIOP ACAOD constraint – daytime and nighttime

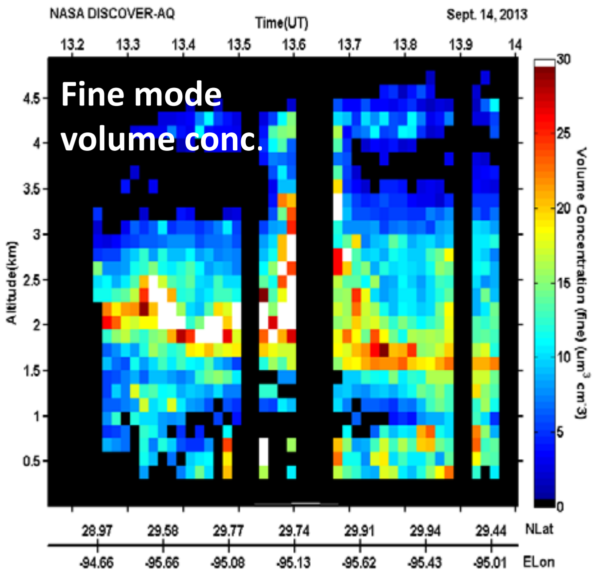
Daytime | Nighttime | Daytime + Nighttime

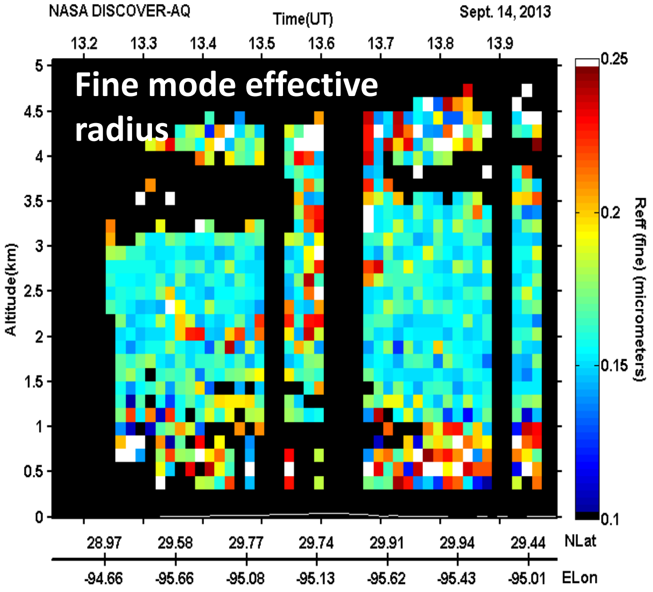


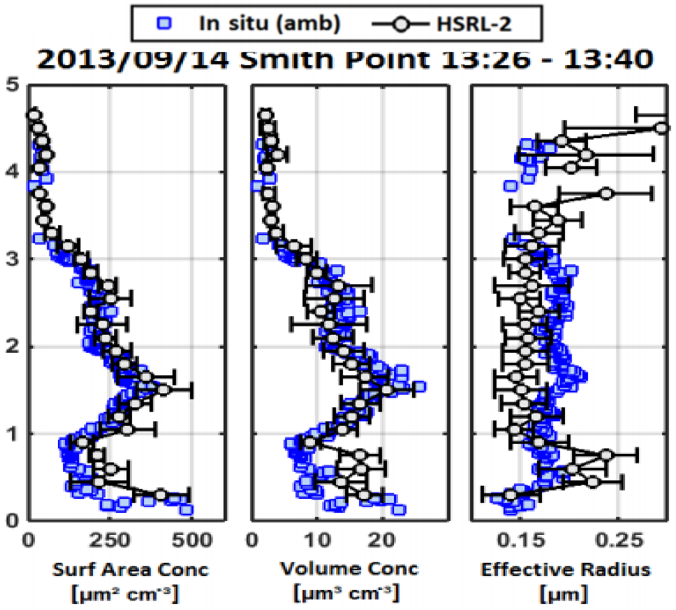
CALIOP V4 operational algorithm (532 nm).

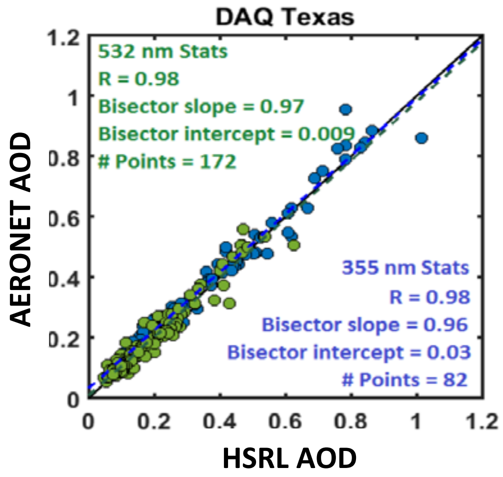
Profiles derived using the ACAOD constraint obtained from the CALIOP opaque water cloud method.

Multiwavelength HSRL aerosol retrieval profiles compare well to coincident airborne in situ measurements







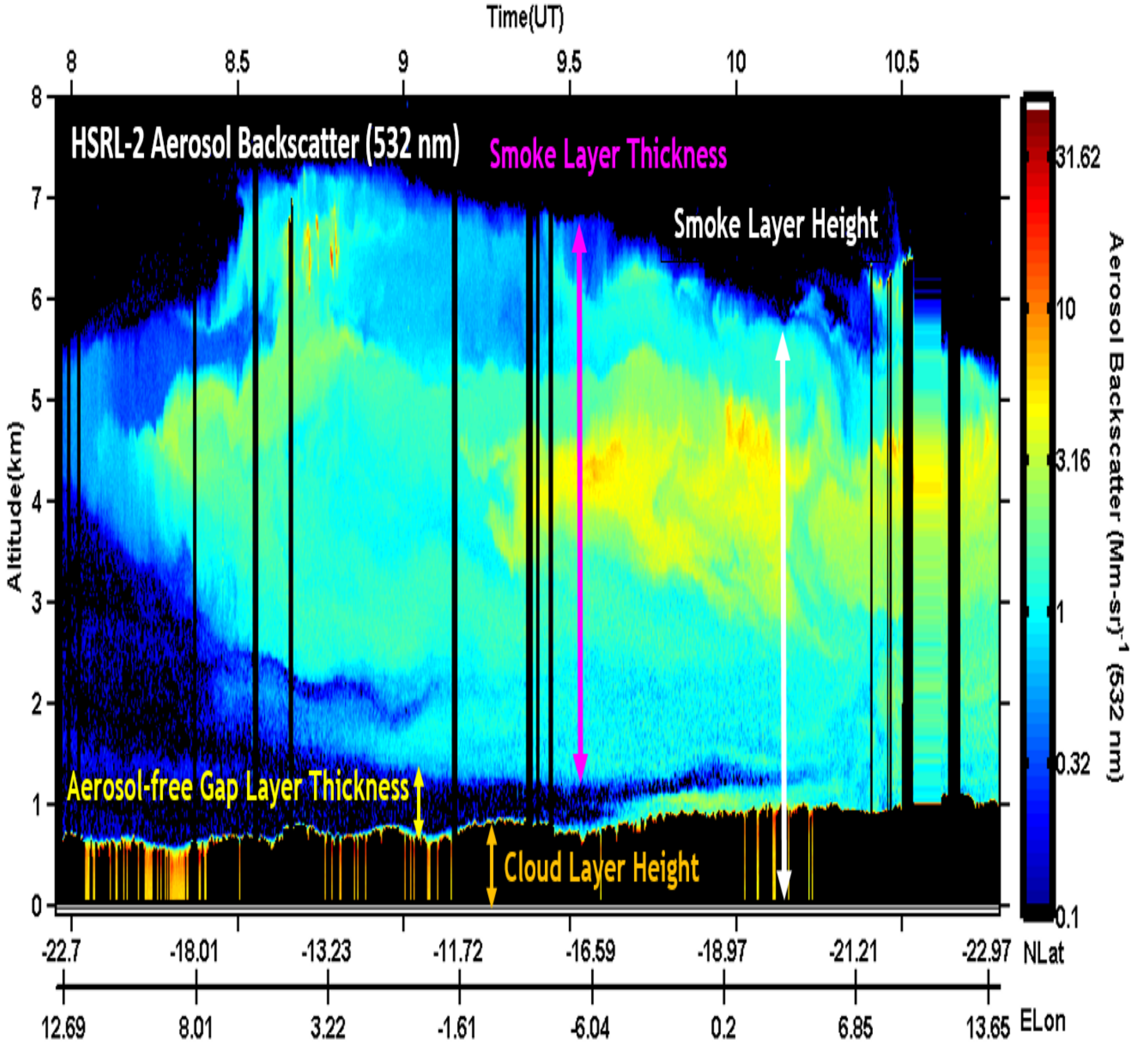


Lidar microphysical retrievals of effective radius and concentrations compare well to airborne in situ measurements

- Relevance of particle size:
  - Improve parameterizations in aerosol transport models
  - Modeling direct radiative effects
  - Indirect effect on cloud radiative properties and precipitation (CCN)
- Relevance of particle concentration:
  - Indirect effects (CCN)
  - Air quality ($PM_{2.5}$)

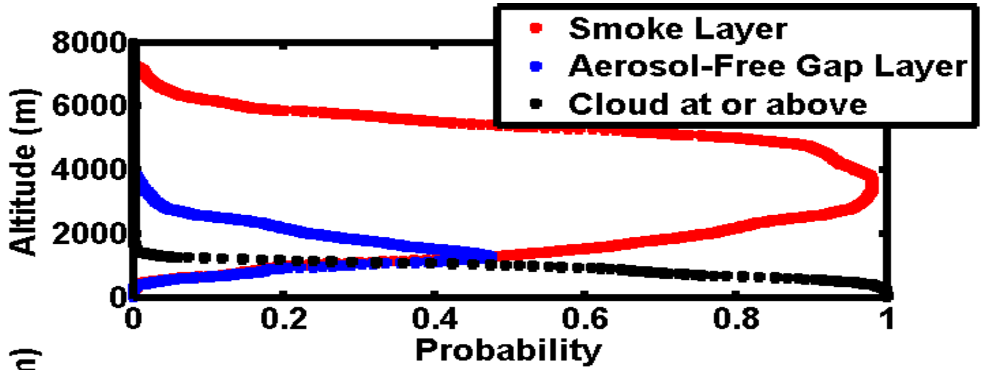
Müller et al., 2014, AMT; Sawamura et al., 2017, ACP

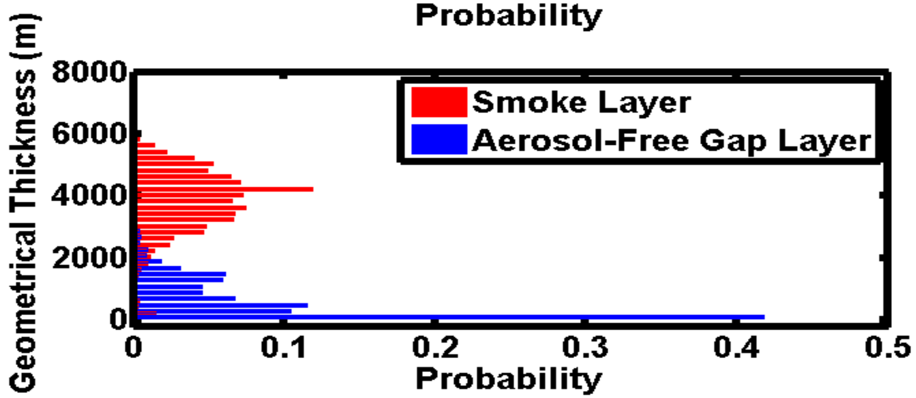
HSRL-2 characterizes smoke layer during ORACLES-2016



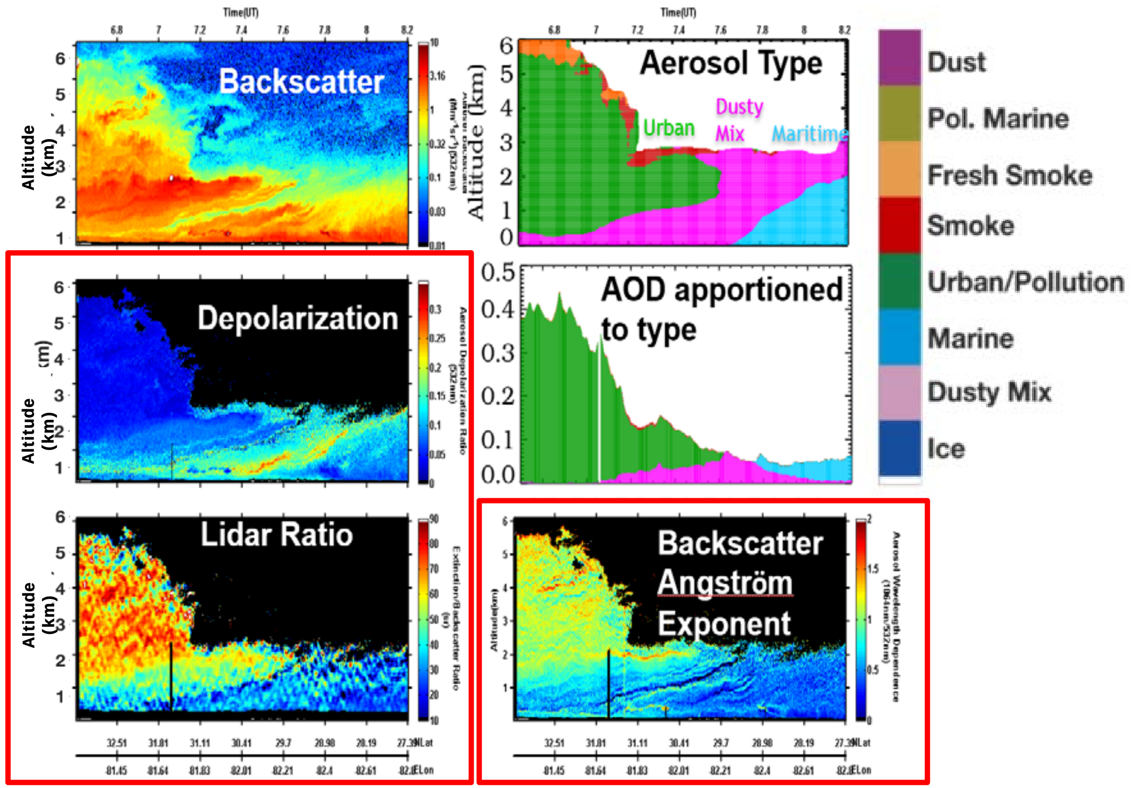
- HSRL-2 aerosol backscatter measurements characterize:
  - smoke and cloud layer heights and thicknesses
  - thickness of the aerosol-free layer between the smoke and cloud layers (i.e. the "gap")
- **Much (>40%) of the time, there is no gap**

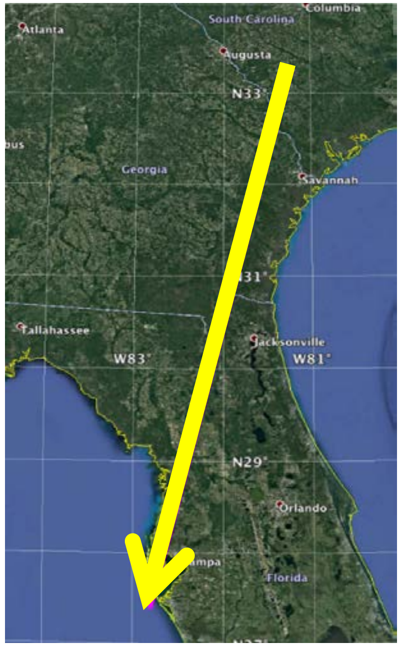
Average over all HSRL-2 ORACLES-016 Flights





HSRL technique enables identification of aerosol type and apportioning optical depth by type



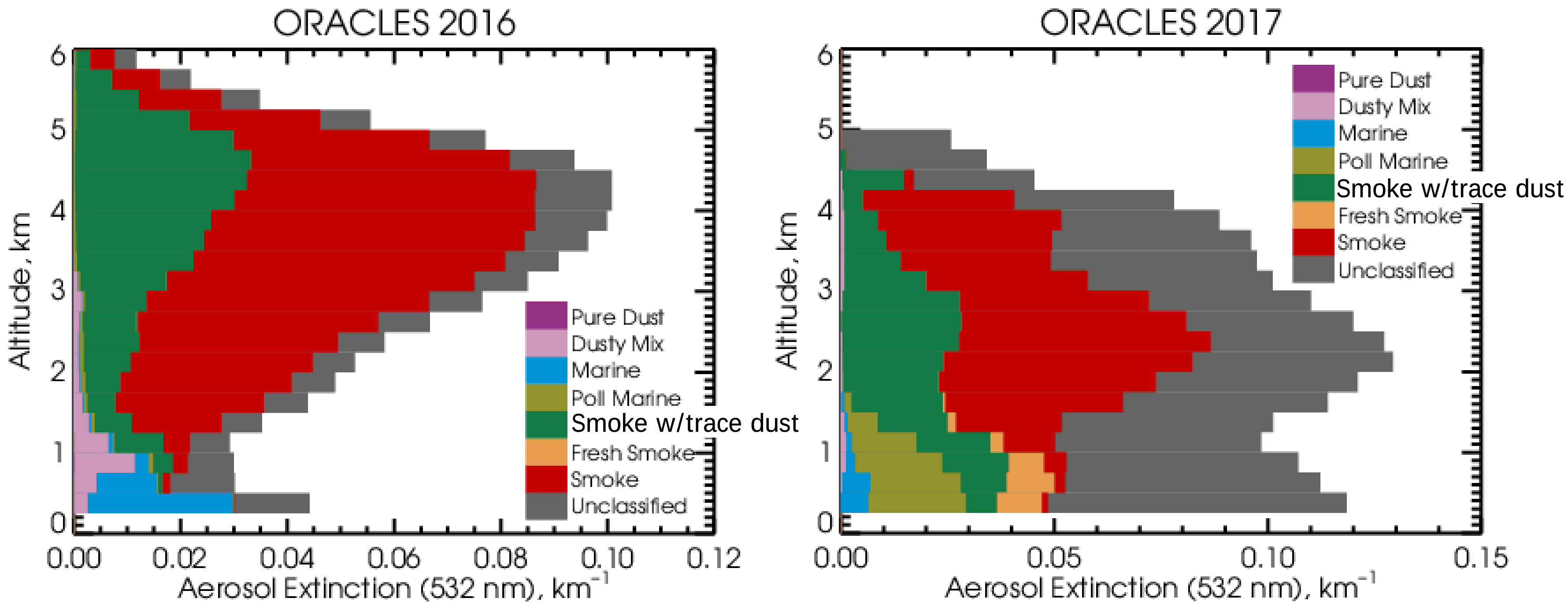


Intensive observables:

- Independent of aerosol amount
- Depends only on aerosol type

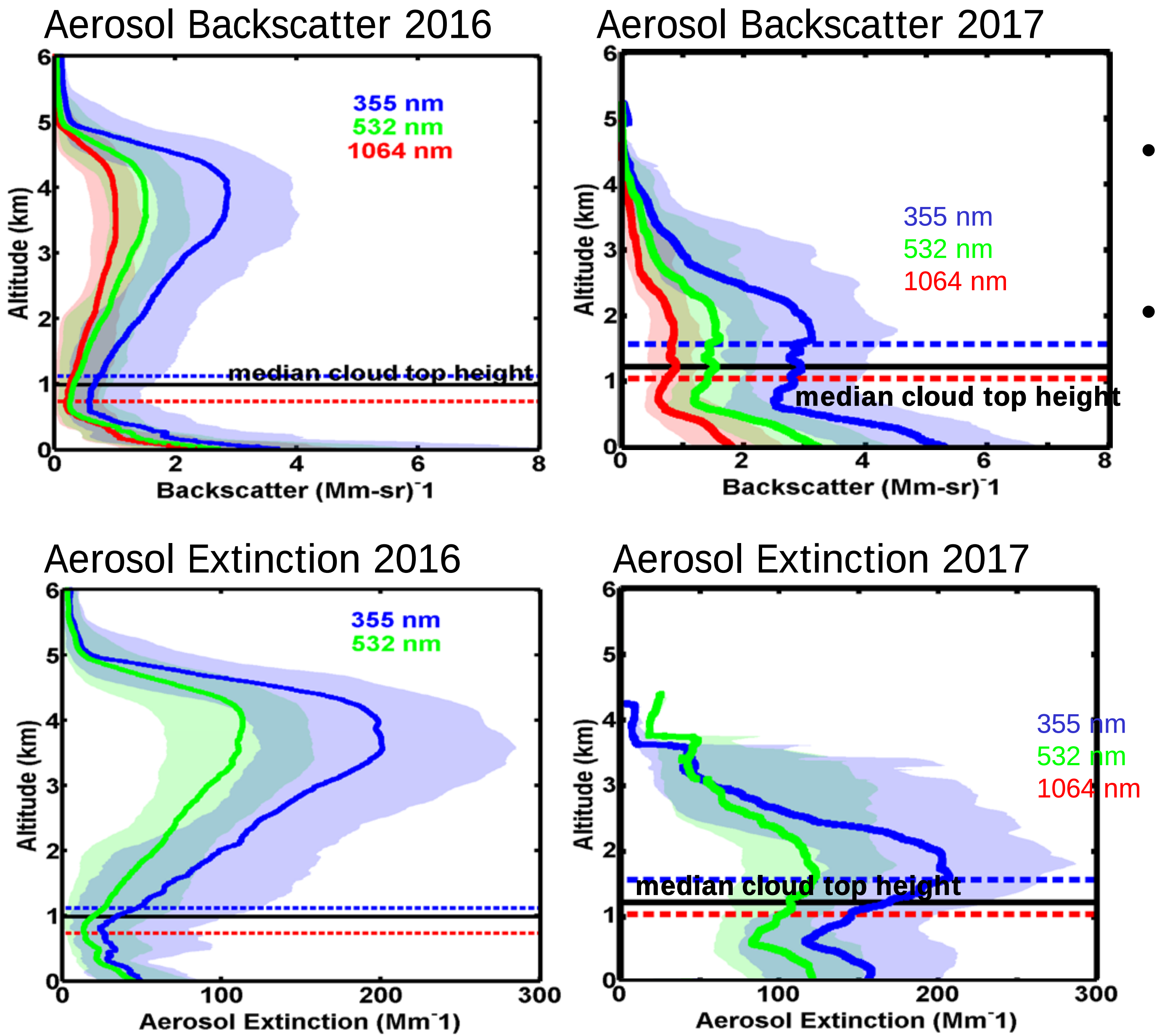
Burton et al., AMT, 2012; 2013

Aerosol types 2016-2017



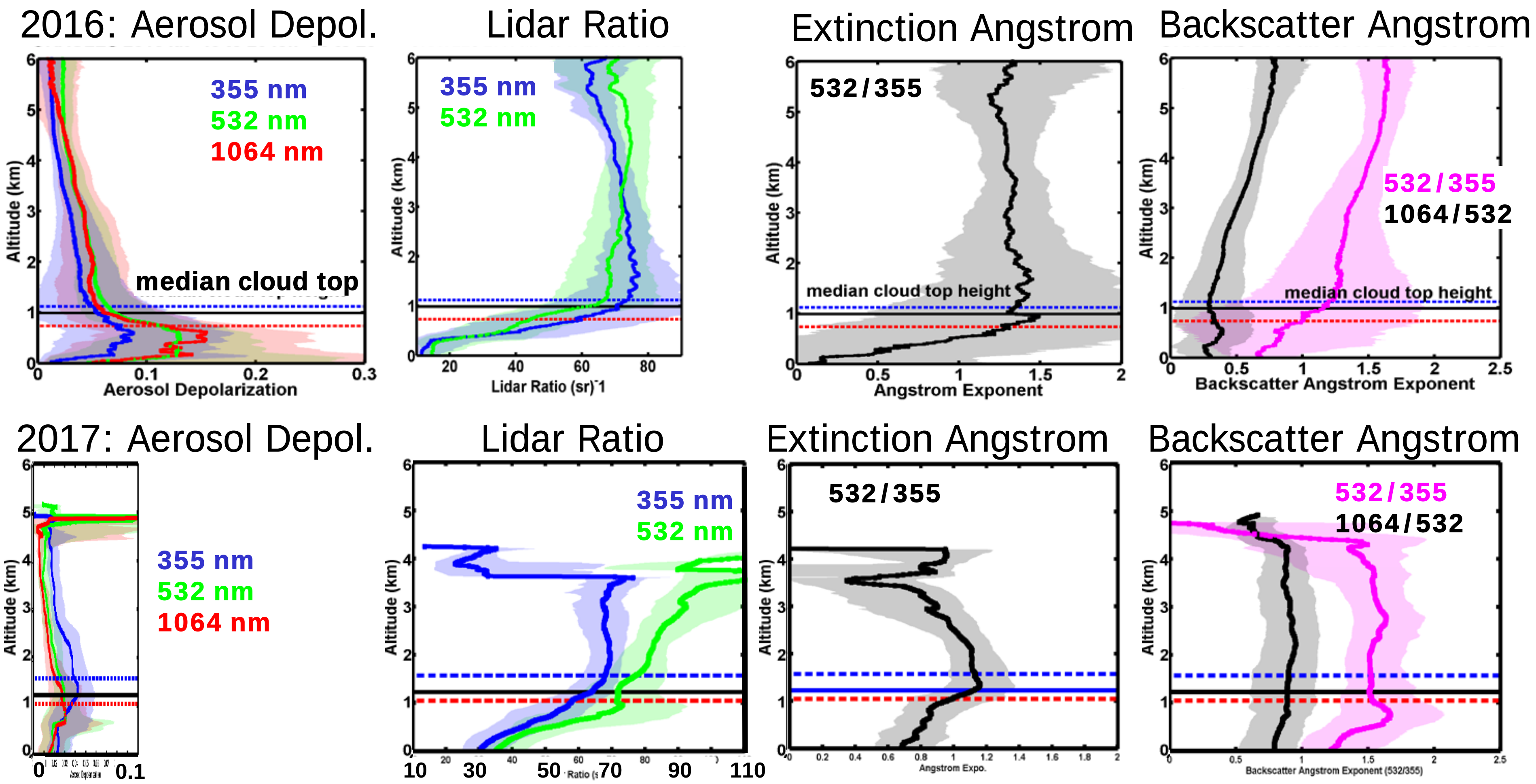
- Smoke plume height higher in 2016 compared to 2017
- More dusty mix in 2016
- Below the clouds, more polluted marine and less clean marine in 2017 (beware sampling)

Backscatter and extinction profiles 2016-2017



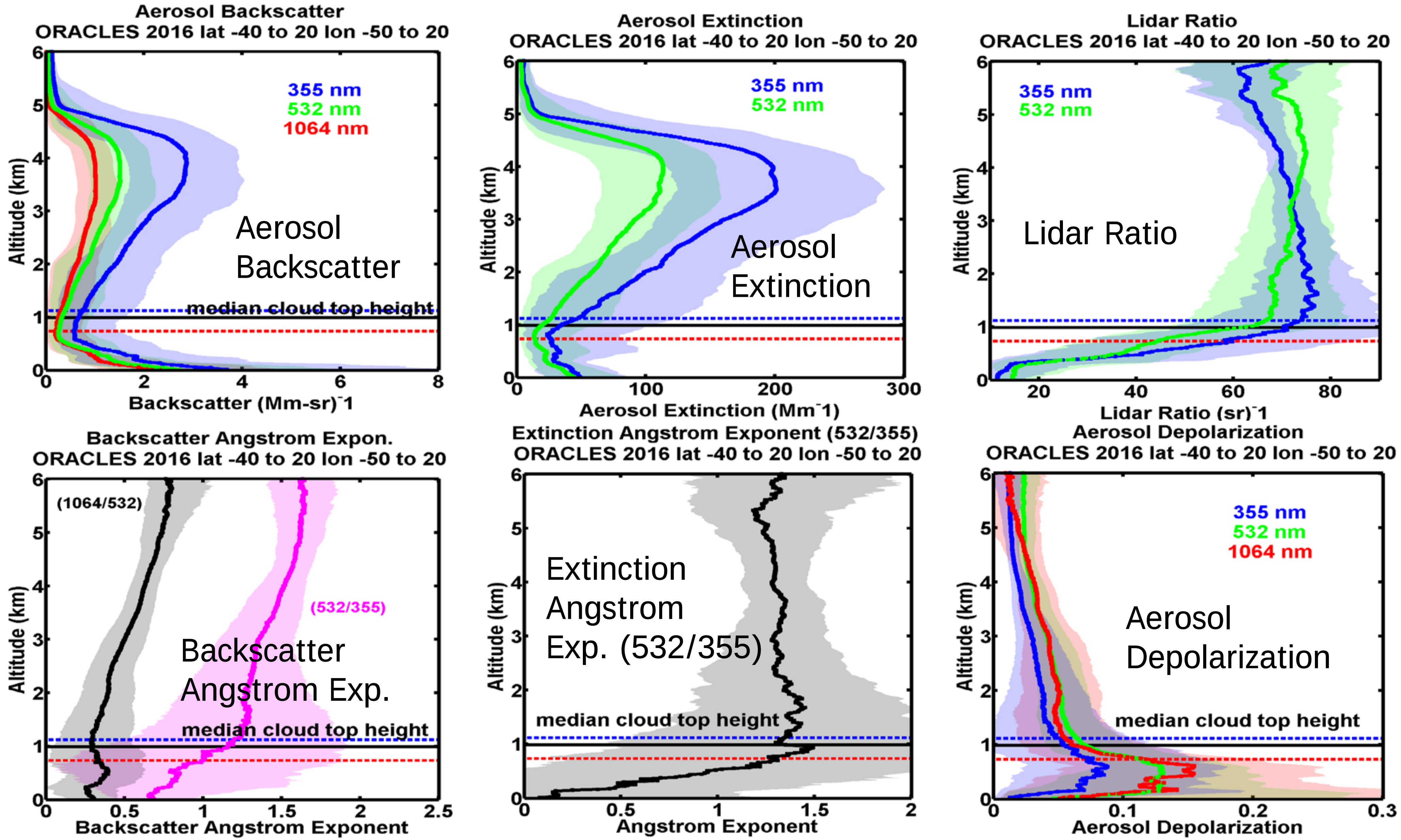
- 2017 smoke layer peak is lower than 2016
- 2017 backscatter and extinction at near-cloud altitudes is larger – not much “gap”

Comparison of observed intensive variables



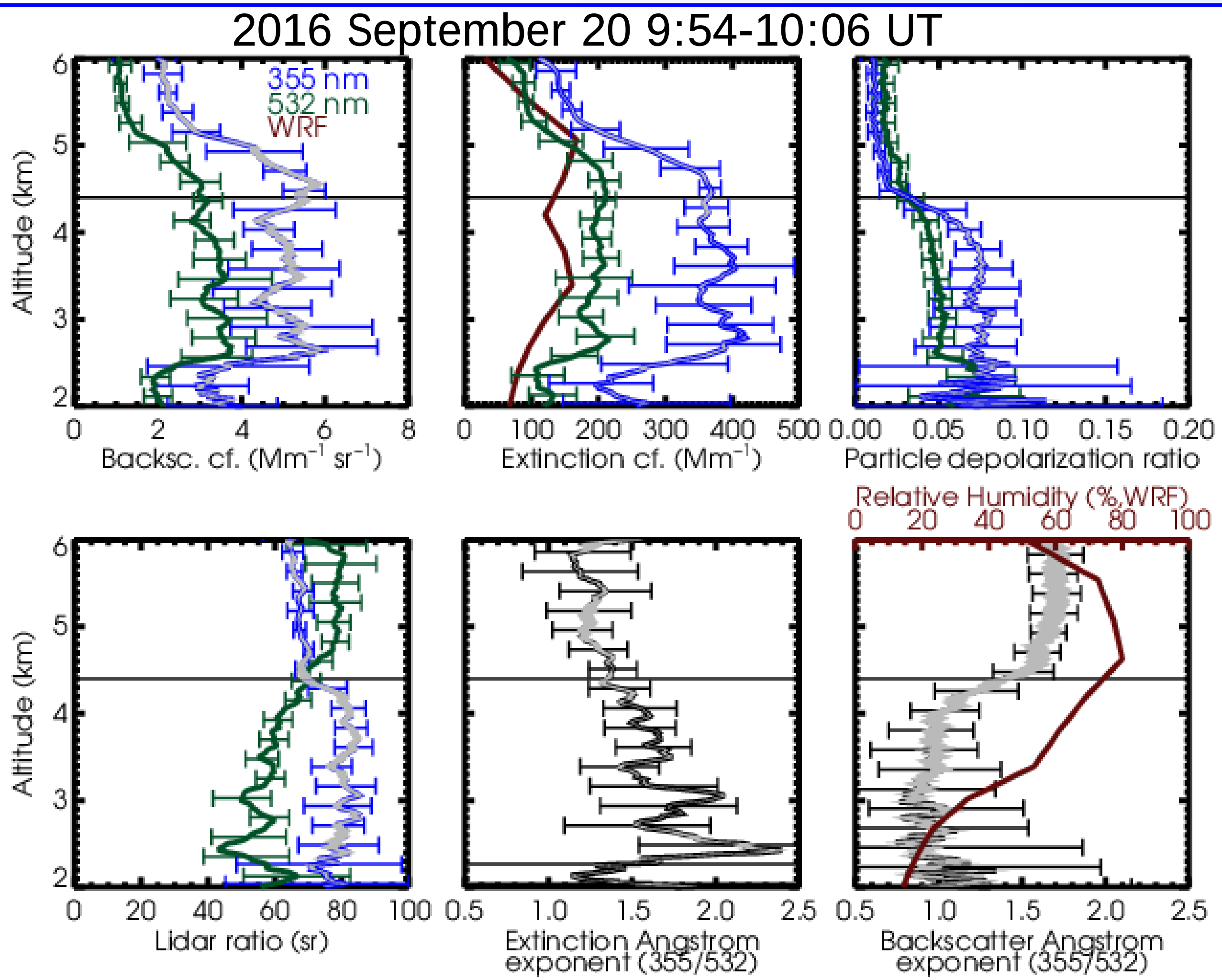
- Size (extinction Angstrom exponent), shape (aerosol depolarization) and composition (lidar ratio)
- Less depolarization in 2017 because less dust
- Differences in lidar ratio, particularly 532 nm lidar ratio in upper part of plume

Median Profiles of Aerosol Properties during ORACLES-2016 from HSRL-2



- About factor of four difference between peak aerosol extinction and aerosol extinction at cloud top
- Small (~10 sr) increase in 532 nm lidar ratio with altitude
- Small (~10 sr) decrease in 355 nm lidar ratio with altitude
- Small (0.25) increase in backscatter Angstrom exp. with altitude
- Relatively constant extinction Angstrom exp.

Vertical variability on 2016 September 20



Below vs. above 4.4 km:

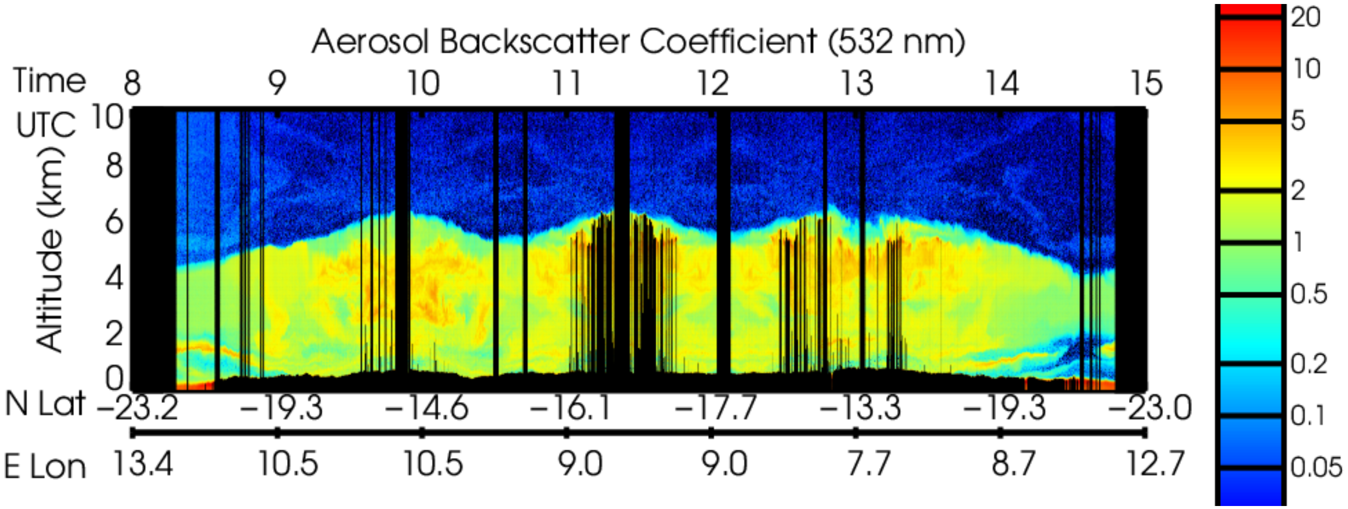
- Some smoke depolarization
- Lidar ratio spectral ratio reverses
- Extinction angstrom exponent suggests smaller particles
- Less relative humidity

Is this "young" smoke?

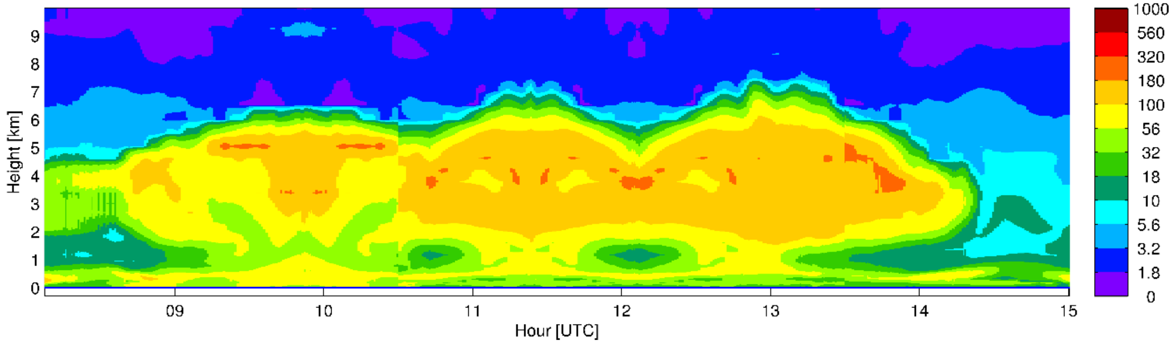
Burton et al. 2018, Calibration of a high spectral resolution lidar using a Michelson interferometer, with data examples from ORACLES, *Applied Optics*, accepted

Smoke age from WRF-AAM

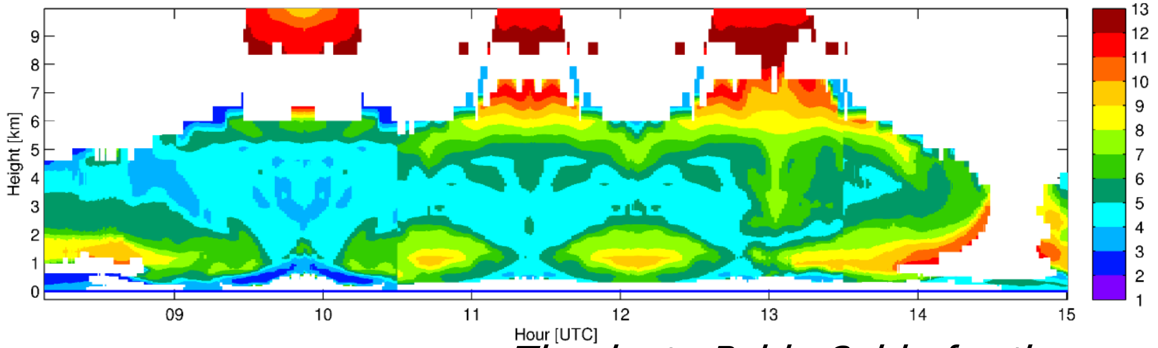
HSRL-2 Backscatter coefficient (532 nm)



WRF-CAM5 Extinction coefficient (532 nm), good agreement for this case

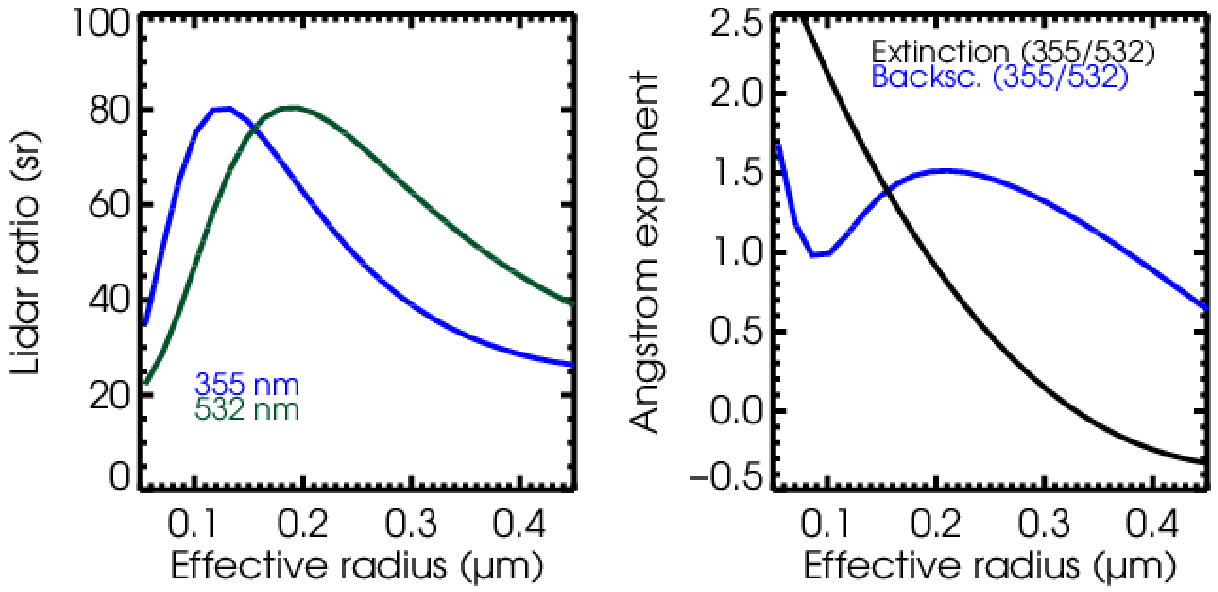


WRF-AAM airmass age, shows top of layer is older, but neither layer is < a few days old



Thanks to Pablo Saide for the model data.

Optical properties from Mie model



- Monomodal log-normal distribution of spherical particles (simple case).
- Effective radius is varied.
- All other variables fixed: effective variance = 0.195, CRI = 1.49-i0.01325 (wavelength independent)

- As effective radius increases, and *nothing else changes*,
  - Extinction angstrom exponent decreases
  - Spectral ratio of lidar ratio reverses

- Conclusion: these optical signatures are primarily related to particle size which may or may not be due to aging

Impacts of Changes in Effective Radius on Lidar Ratio and Angstrom Exponent

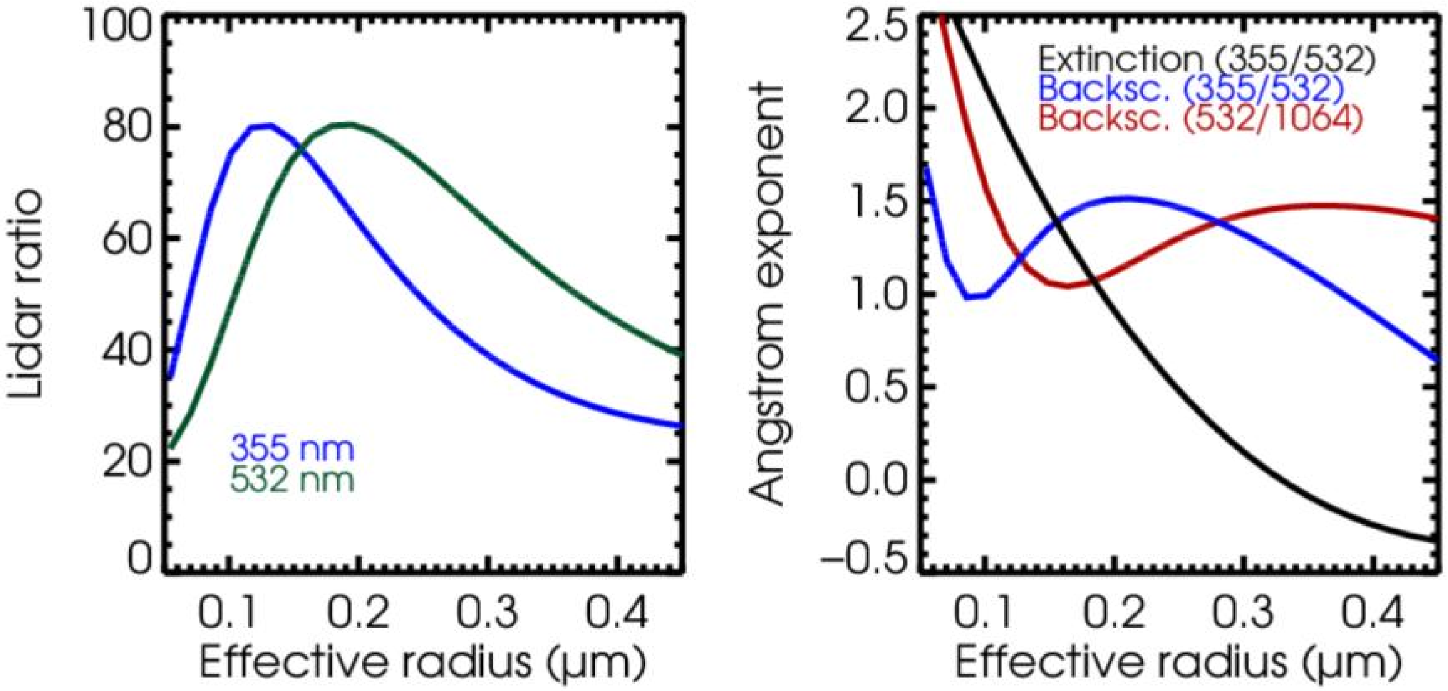
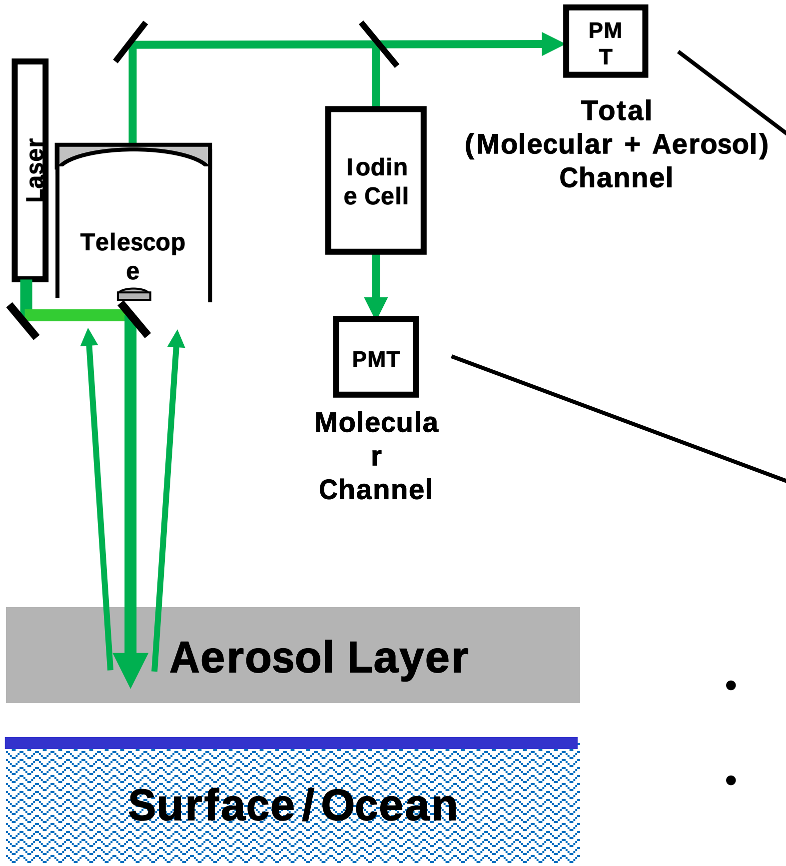
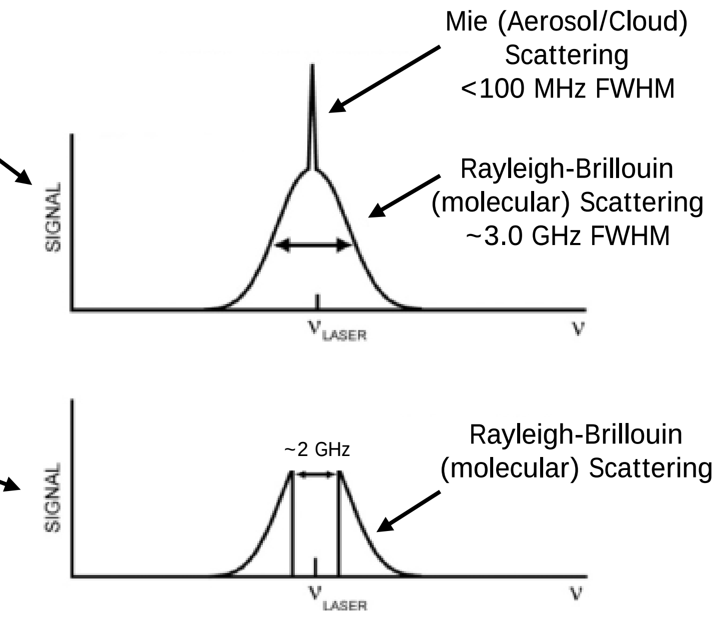


Figure 13. Theoretical results from Mie modeling of various lidar intensive parameters for a monomodal log-normal distribution with varying effective radius. Effective variance is held fixed at 0.195 and refractive index is wavelength independent and held fixed at 1.49-i0.01325. In the left panel are shown the lidar ratio at 355 nm (blue) and 532 nm (green) and in the right panel are Ångström exponents: extinction-related Ångström exponent between 355 and 532 nm (black), backscatter-related Ångström exponent between 355 and 532 nm (blue) and between 532 and 1064 nm (red).

(Burton et al., 2018, submitted to Appl. Optics)

High Spectral Resolution Lidar (HSRL) technique for aerosol profiling



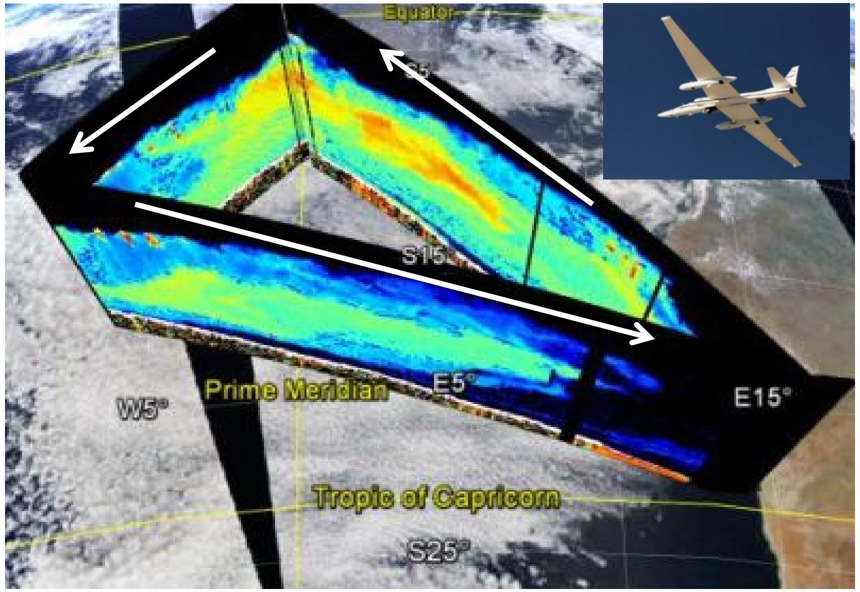


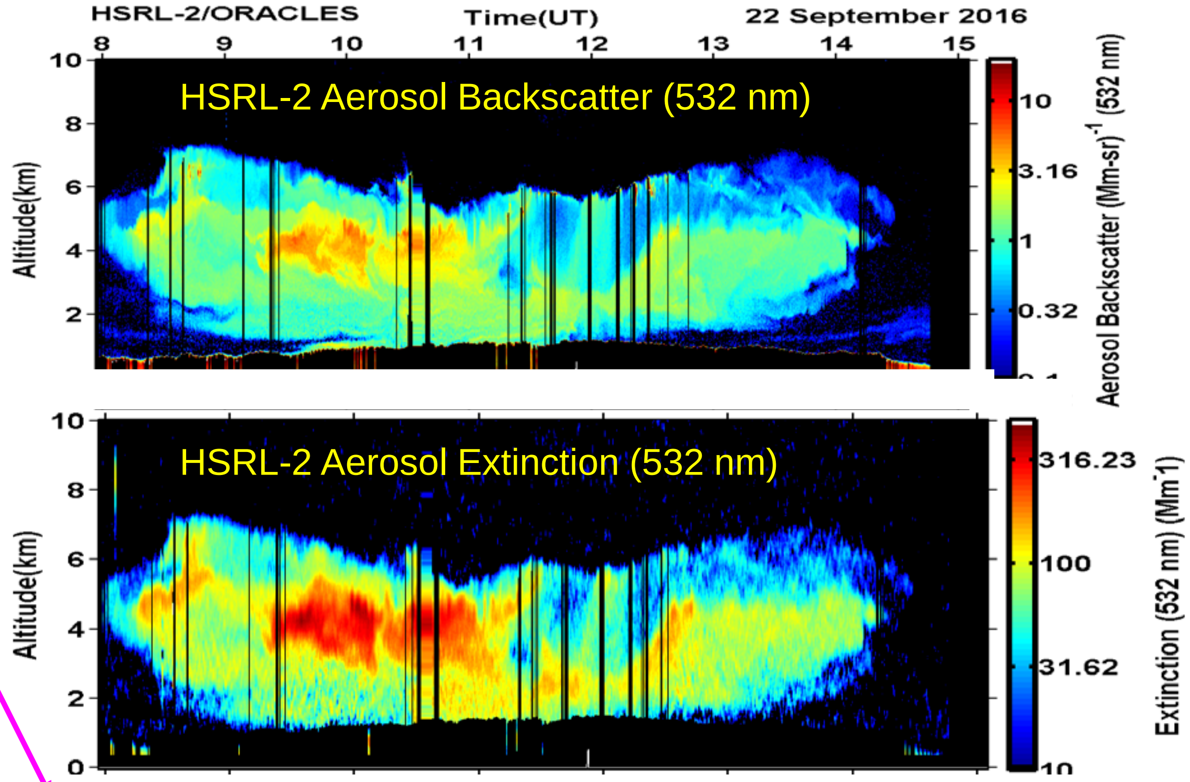
- Tuning laser to an I_2 absorption line blocks particulate backscatter from “Molecular Channel”
- 2 channels enable 2 equations to solve for 2 unknowns: aerosol backscatter and extinction

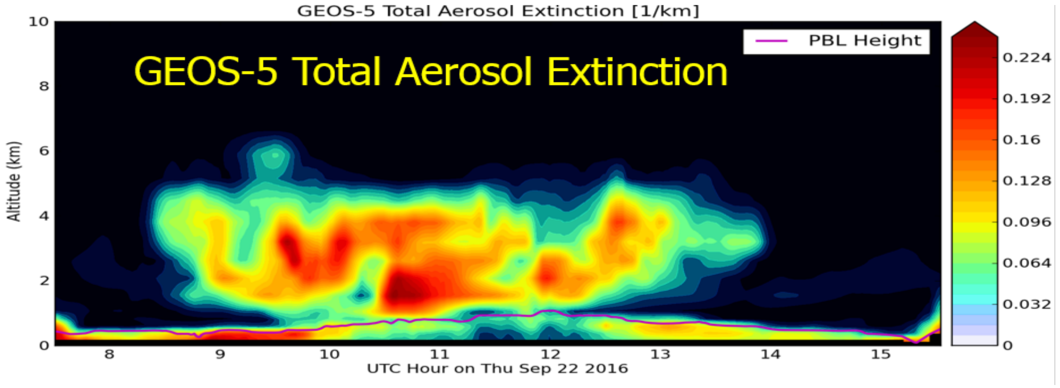
Airborne NASA LaRC HSRL-2 measures smoke distribution and properties for model evaluation during NASA ORACLES Mission

- ORACLES Earth Venture Suborbital mission
- Target: Extensive biomass smoke plume over persistent stratus cloud deck off the west coast of Africa
  - Smoke has significant radiative effect: localized absorption and impacts cloud microphysics
- During first ORACLES mission, GEOS-5 model smoke plume was systematically lower than HSRL-2 observations (da Silva - GSFC)

HSRL-2 Aerosol Backscatter (532 nm)

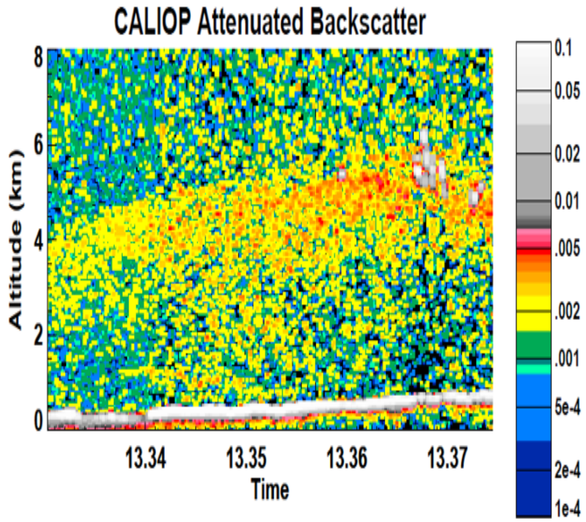


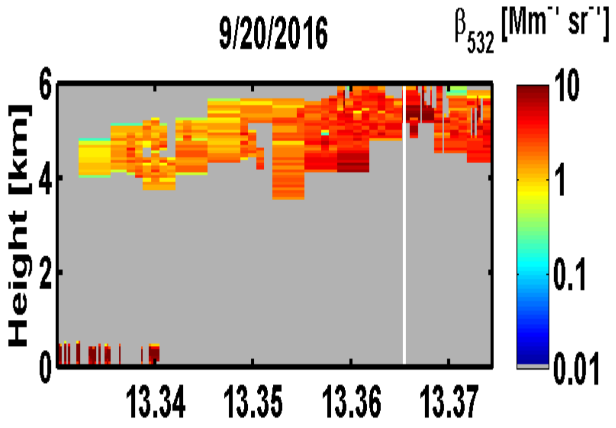




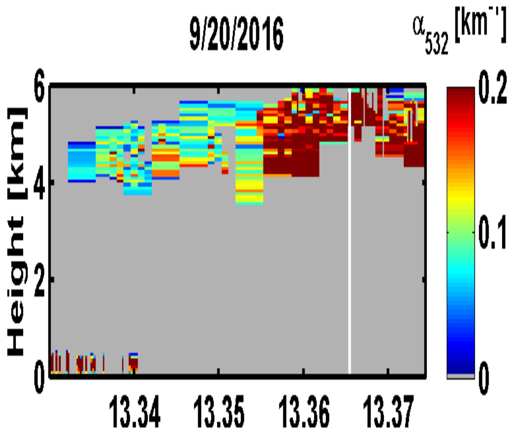
Where CALIPSO identifies smoke, CALIPSO operational retrievals agree with HSRL-2

"...wonderful illustration of what we don't do so well (detection)." (Mark Vaughan- CALIPSO team)



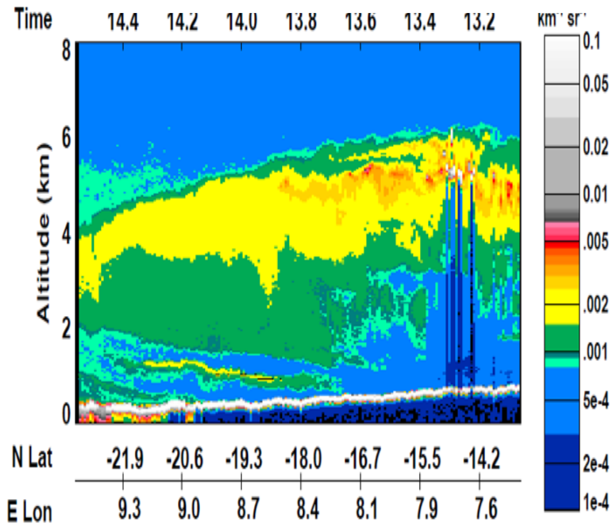


CALIPSO aerosol backscatter

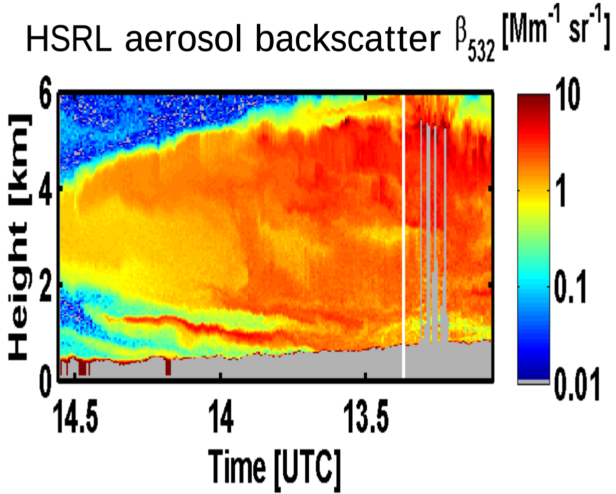


CALIPSO aerosol extinction

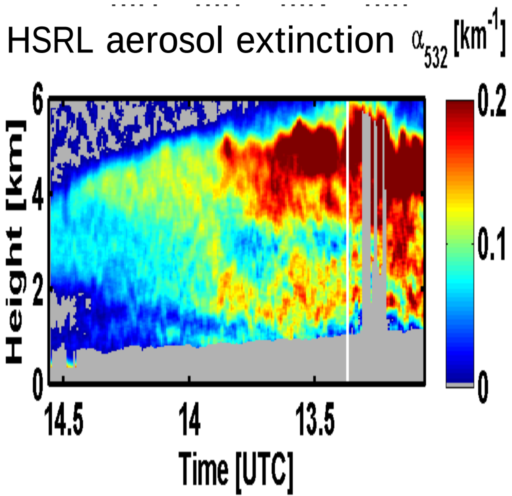
HSRL attenuated backscatter



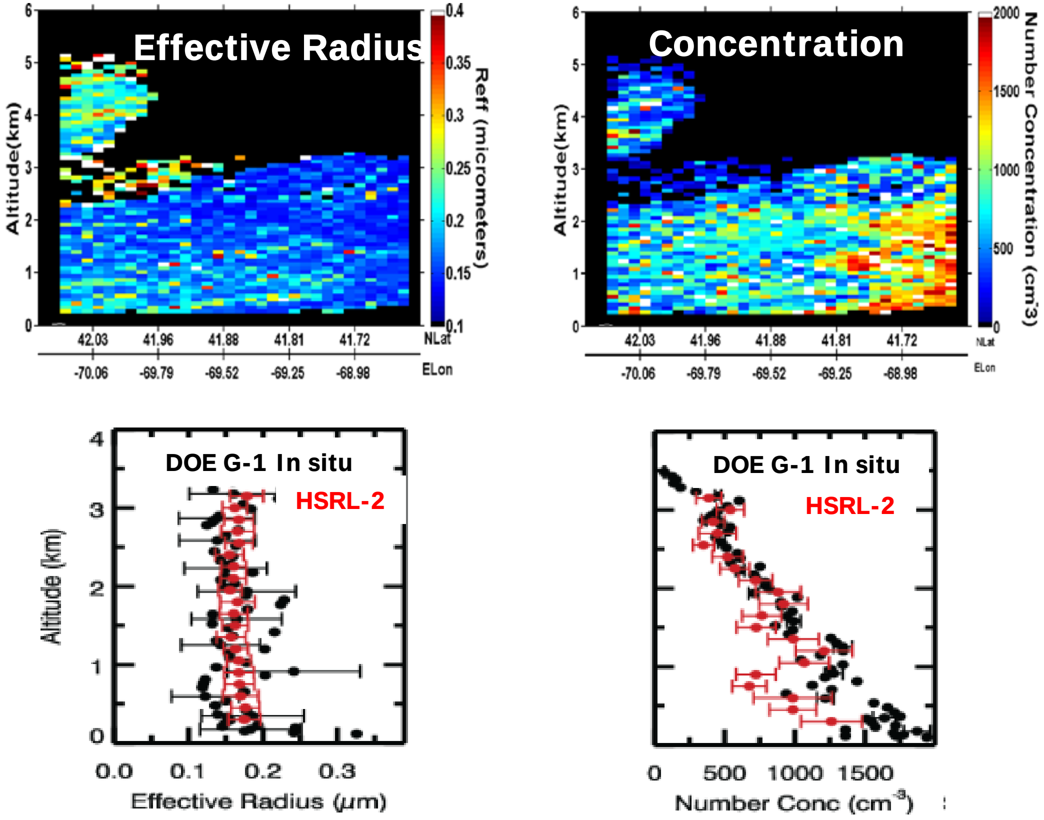
HSRL aerosol backscatter



HSRL aerosol extinction



Increased information content from multiwavelength HSRL enables retrievals of aerosol microphysical parameters



- Why do we care about aerosol size and concentration?
  - Relevance of particle size:
    - Improve parameterizations in aerosol transport models
    - Modeling direct radiative effects
    - Indirect effect on cloud radiative properties and precipitation (CCN)
  - Relevance of particle concentration:
    - Indirect effects (CCN)
    - Air quality ($PM_{2.5}$)

Müller et al., 2014, Atmospheric Measurement Techniques. doi:10.5194/AMT-7-3487-2014