HSRL-2 Measurements During ACTIVATE November 1, 2021

Rich Ferrare, John Hair, Chris Hostetler, Taylor Shingler, Dave Harper, Shane Seaman, Marta Fenn, Marian Clayton, Sharon Burton, Amy Jo Scarino, Tony Cook, Rob Ryan, Mark Vaughan, Snorre Stamnes, Lee Thornhill, Luke Ziemba, Seethala Chellappan, Paquita Zuidema

LaRC Airborne High Spectral Resolution Lidar – Generation 2 ("HSRL-2")

See https://www-air.larc.nasa.gov/missions/activate/docs/data_workshop/Hostetler.pdf for a description of HSRL2 measurements and products

Data Products

hdf5 data and png plot images

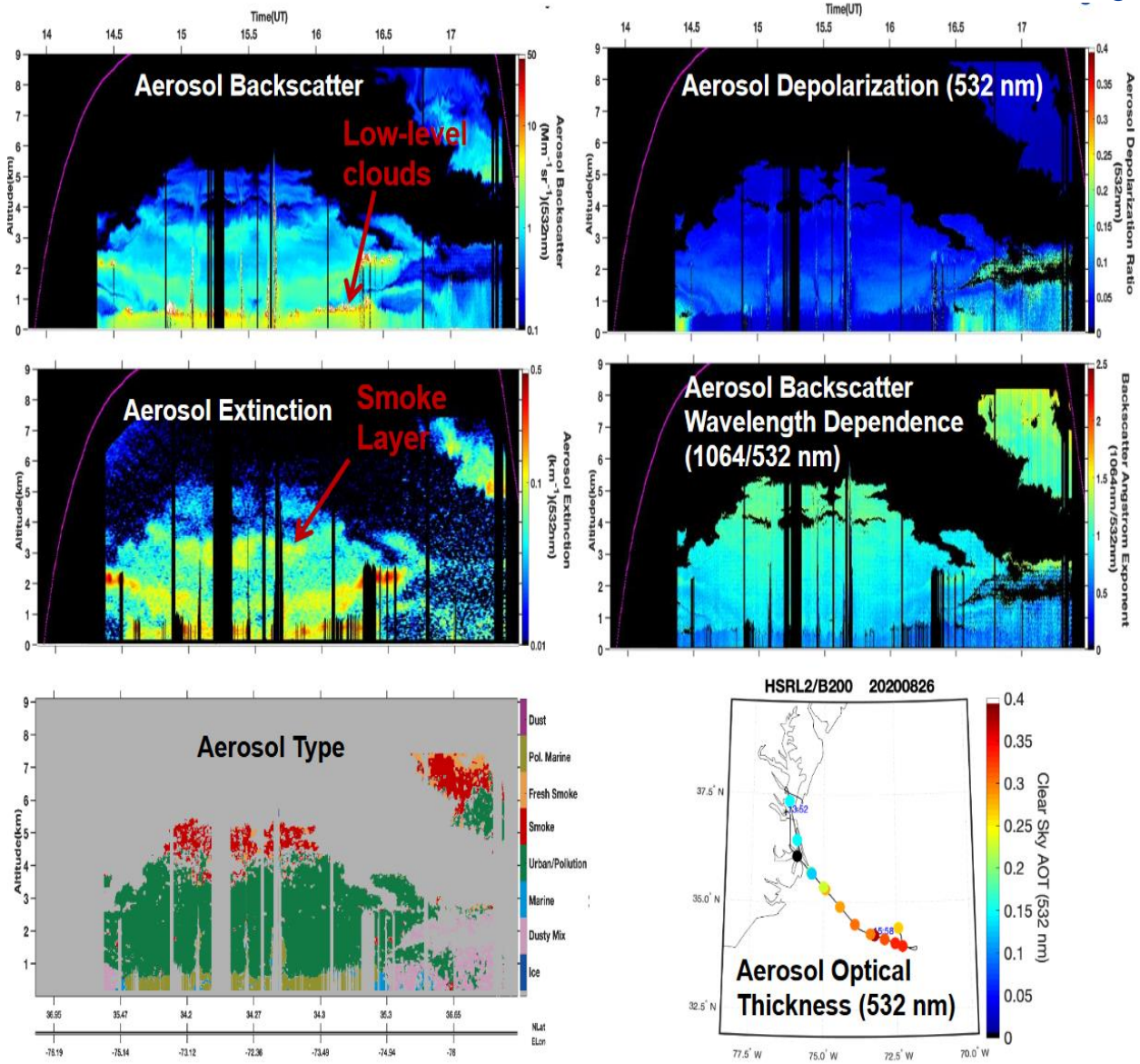
- Aerosol Extensive Measurements
  - Particulate backscatter profiles (355, 532, 1064 nm)
    - Δx ~ 1 km, Δz ~ 15 m
  - Aerosol extinction profiles and AOT (355 and 532 nm)
    - Δx ~ 6 km, Δz ~ 315 m
- Aerosol Intensive measurements
  - Particle depolarization profiles (355, 532, 1064 nm)
    - Δx ~ 1 km, Δz ~ 15 m
  - Extinction-to-backscatter ratio profiles (355 and 532 nm)
    - Δx ~ 6 km, Δz ~ 315 m
  - Angstrom exponent profiles
    - Extinction: 355-532 (Δx ~ 6 km, Δz ~ 315 m)
    - Backscatter 355-532, 532-1064 (Δx ~ 1 km, Δz ~ 15 m)
- Aerosol Type
- Aerosol Optical Thickness
- Cloud top heights
- Cloud top extinction and lidar ratios (future)

ICARTT format

- Mixed Layer Heights
- Aerosol Optical Thickness

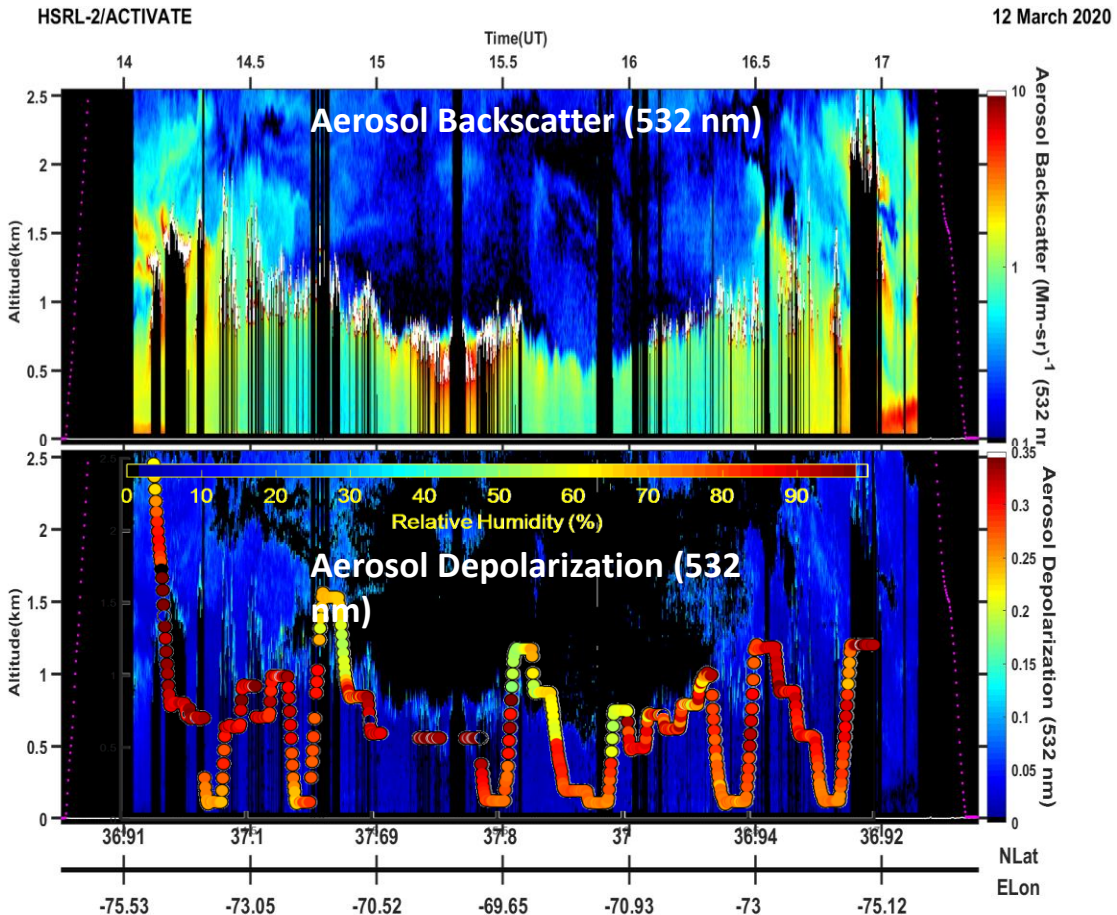
Data archived at https://www-air.larc.nasa.gov/cgi-bin/ArcView/activate.2019#HOSTETLER.CHRIS/

Look for
ACTIVATE-HSRL2_UC12_2020_R0_Rad_Me_First.pdf
ACTIVATE-HSRL2_UC12_2020_R0_DataFilleDescription.pdf

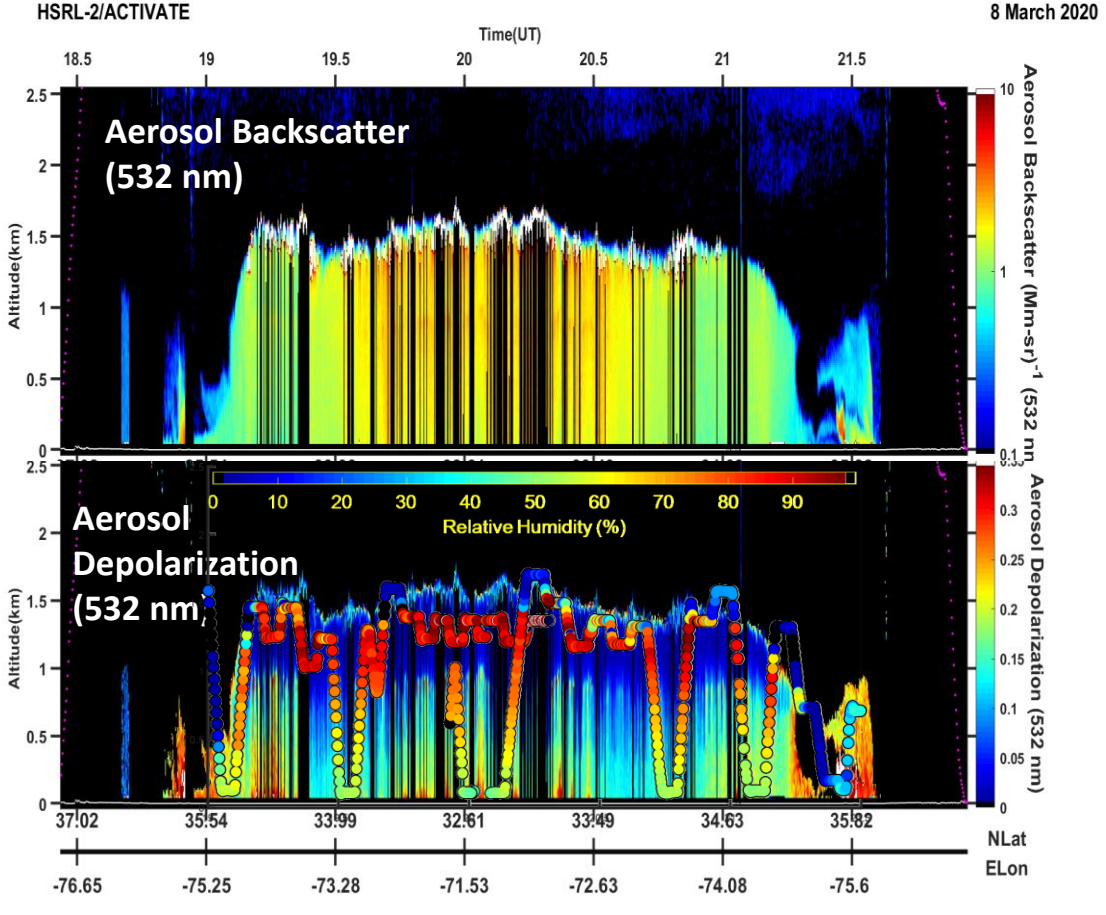


HSRL2 Observations of Enhanced Depolarization over the Ocean

- Typically HSRL2 measures low aerosol depolarization over the ocean. This is associated with spherical sea salt aerosols.
- Note the high (>65%) relative humidity (RH) in the lowest 1 km derived from airborne in situ (Diode Laser Hygrometer-DLH) measurements on the Falcon aircraft

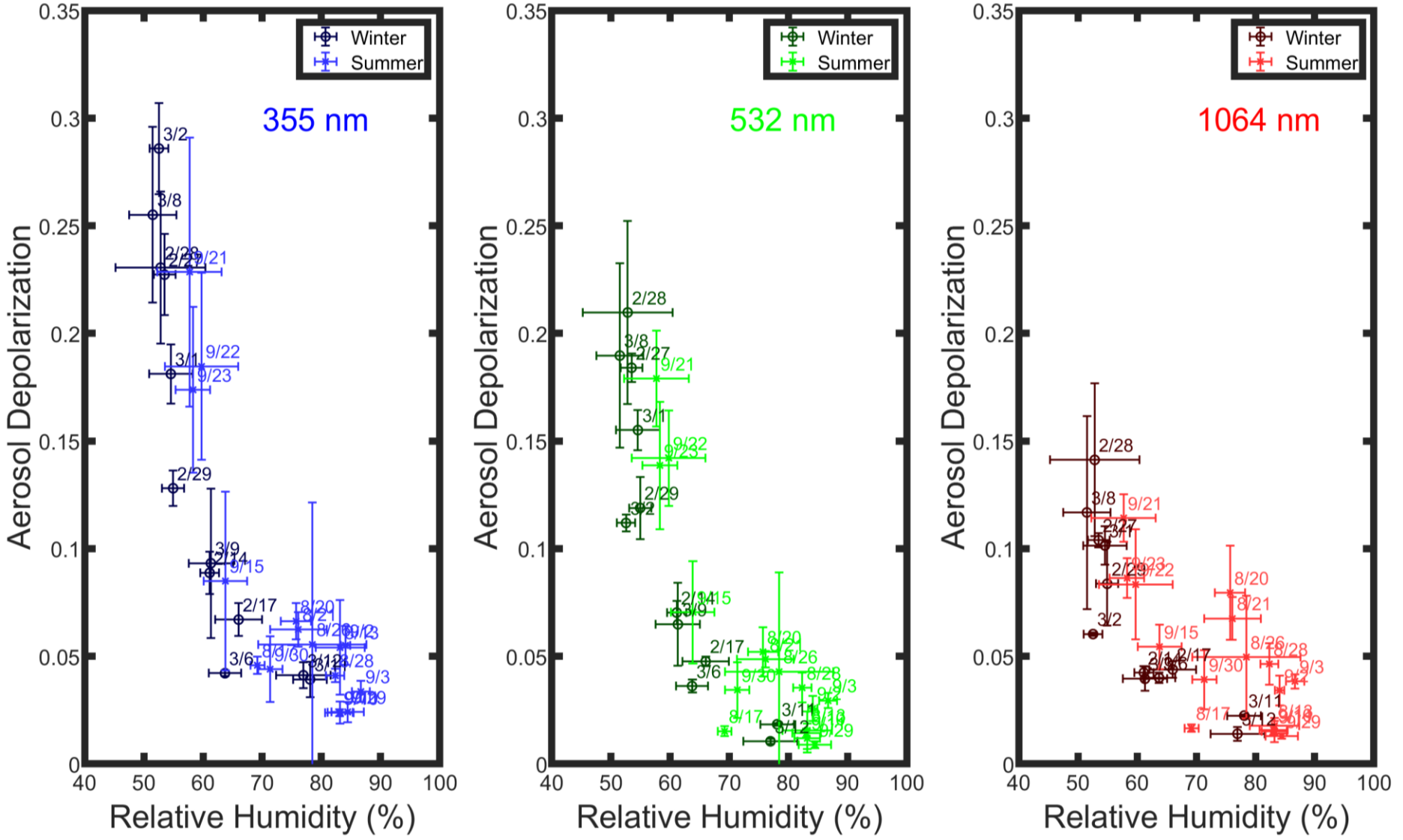


- In contrast, during several ACTIVATE flights during the winter and summer campaigns, HSRL2 measured elevated (>10-15%) aerosol depolarization in the lowest 1 km. Note the lower (<60%) relative humidity (RH) derived from the airborne in situ DLH measurements on the Falcon aircraft



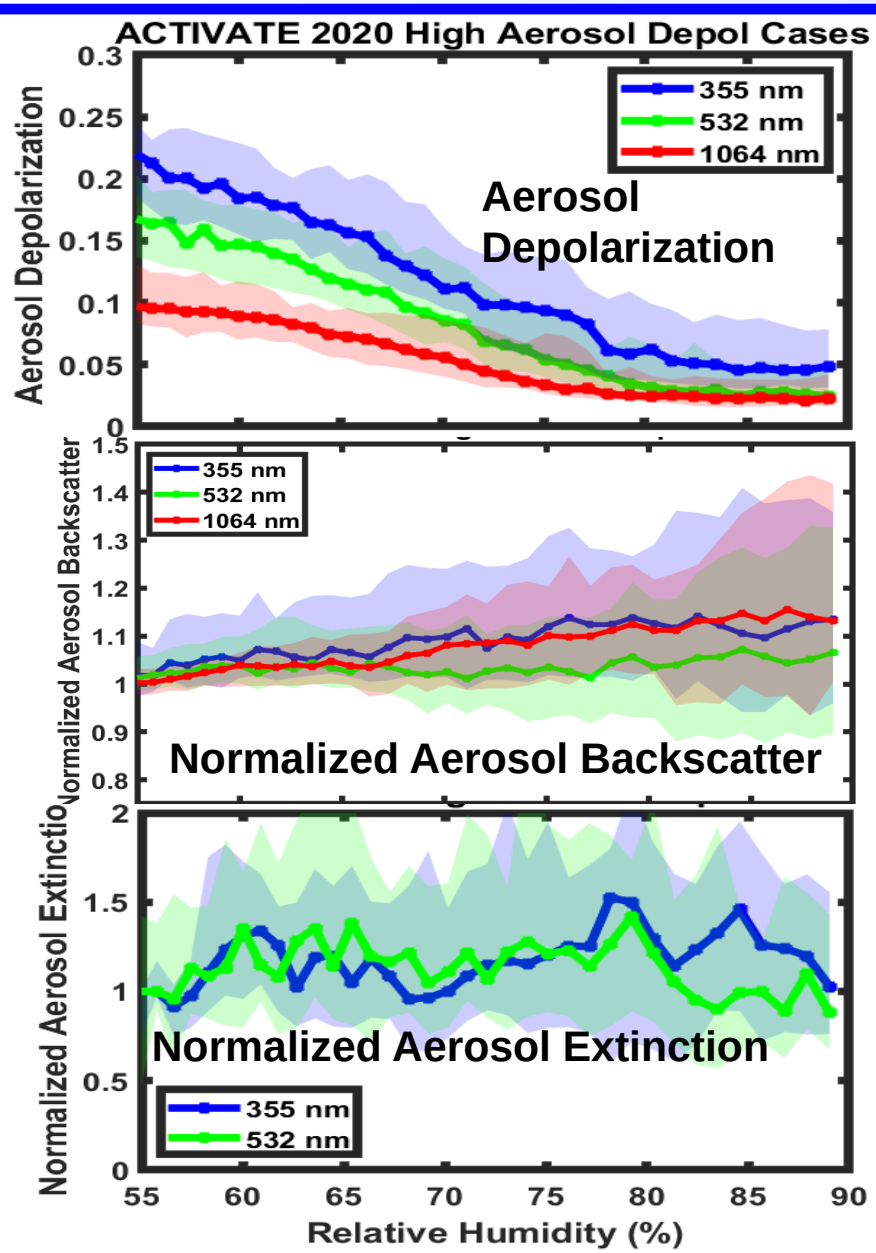
HSRL2 Measurements During ACTIVATE 2020 Show Elevated Aerosol Depolarization when RH below about 60%

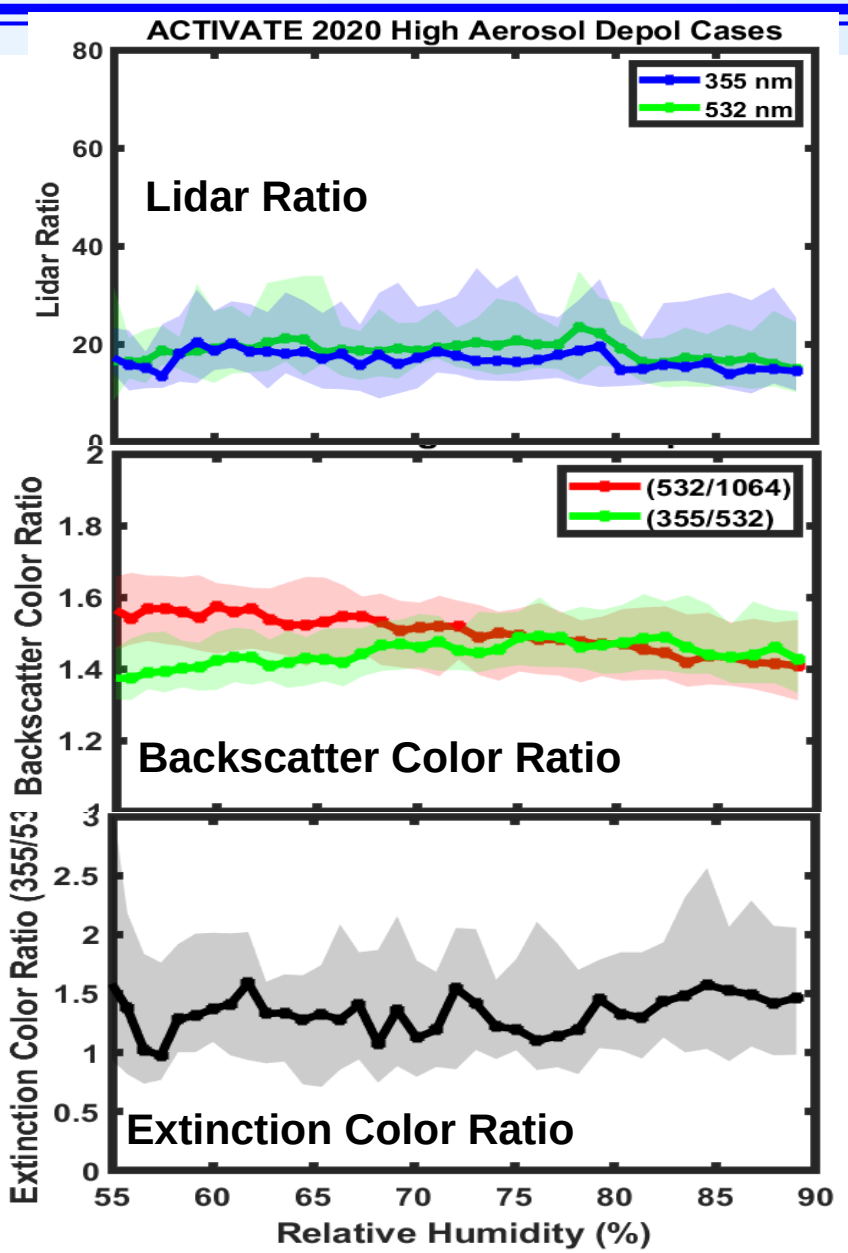
- Average depolarization in lowest 20% of Mixed Layer coincident with dropsondes
- Each point represents average for that date
- High aerosol depolarization is associated with RH below about 60%
- Depolarization decreases with increasing wavelength
- Elevated depolarization during both winter and summer



HSRL2 Measurements of Aerosol Optical Properties as a function of RH for Cases of High Aerosol Depolarization during ACTIVATE

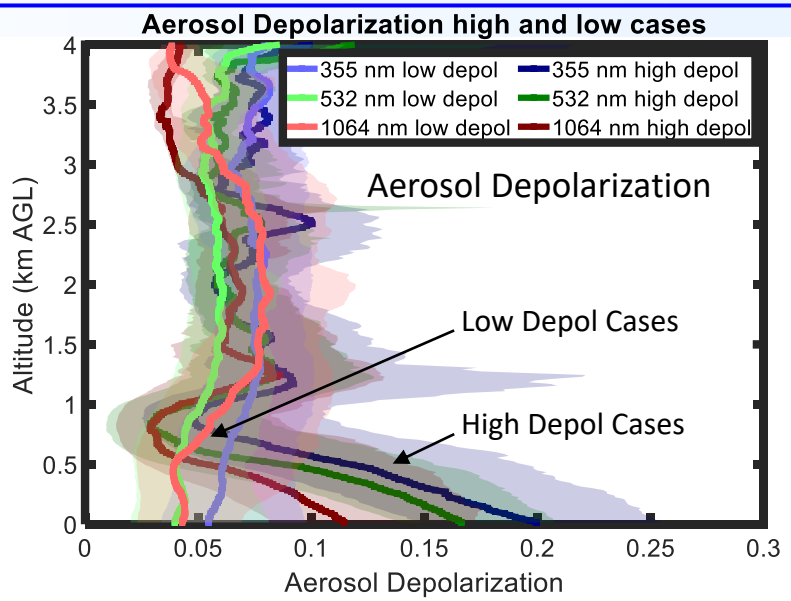
- Cases where aerosol depol (532 nm) > 0.1
- Nearly constant water vapor mixing ratio (conservative tracer) to reduce changes due to changes in air mass
- Changes in RH due to changes in temperature
- Significant changes in aerosol shape as shown by changes in aerosol depolarization
- Apparently minimal changes in aerosol size as shown by nearly constant color ratios and lidar ratio

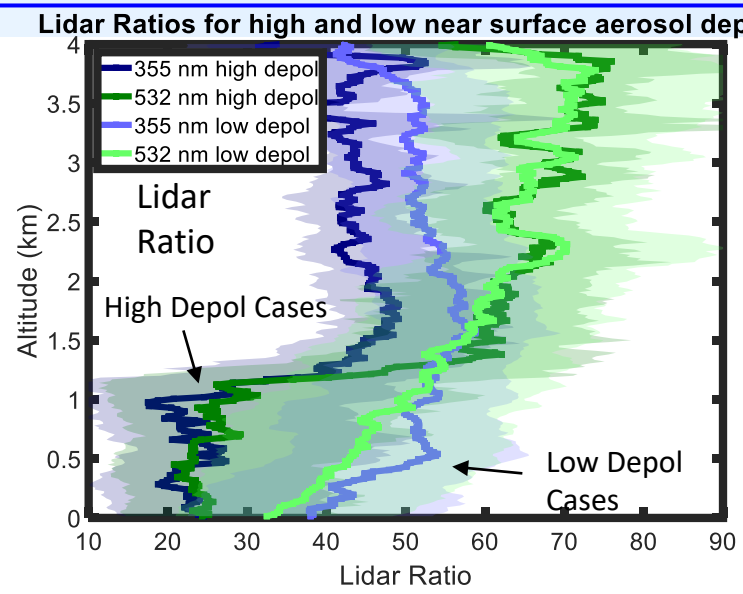


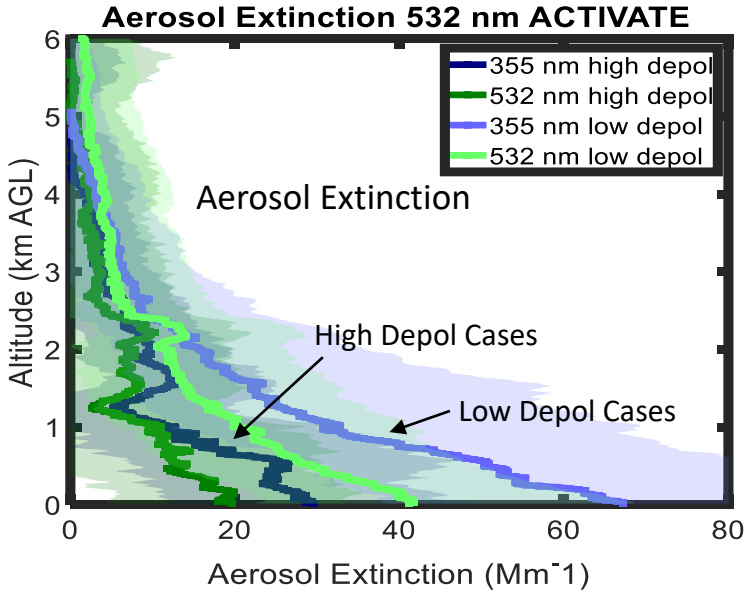


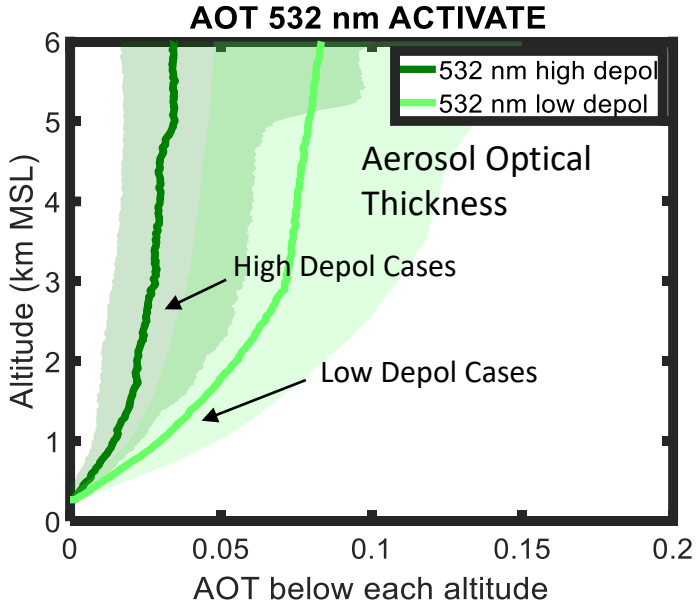
Aerosol Properties (High vs. Low Aerosol Depolarization)

- HSRL2 data from 2020 divided into high and low near-surface depolarization cases
- High depolarization observed in about 18% of the HSRL2 profiles and during 23 of 33 flights
- Median lidar ratios at 355 and 532 nm were around 20-25 sr during these high depol (nonspherical sea salt) cases
- Higher lidar ratios observed when other aerosol types (e.g. smoke) within BL
- On average, lidar ratio increased significantly with altitude
- Median AOT (0-7 km) for high depol cases was about 0.04 (532 nm)
- Median AOT (0-7 km) for low depol cases was about 0.09 (532 nm)
- AOT contributed by the nonspherical sea salt particles was small (0.03-0.04) (532 nm)



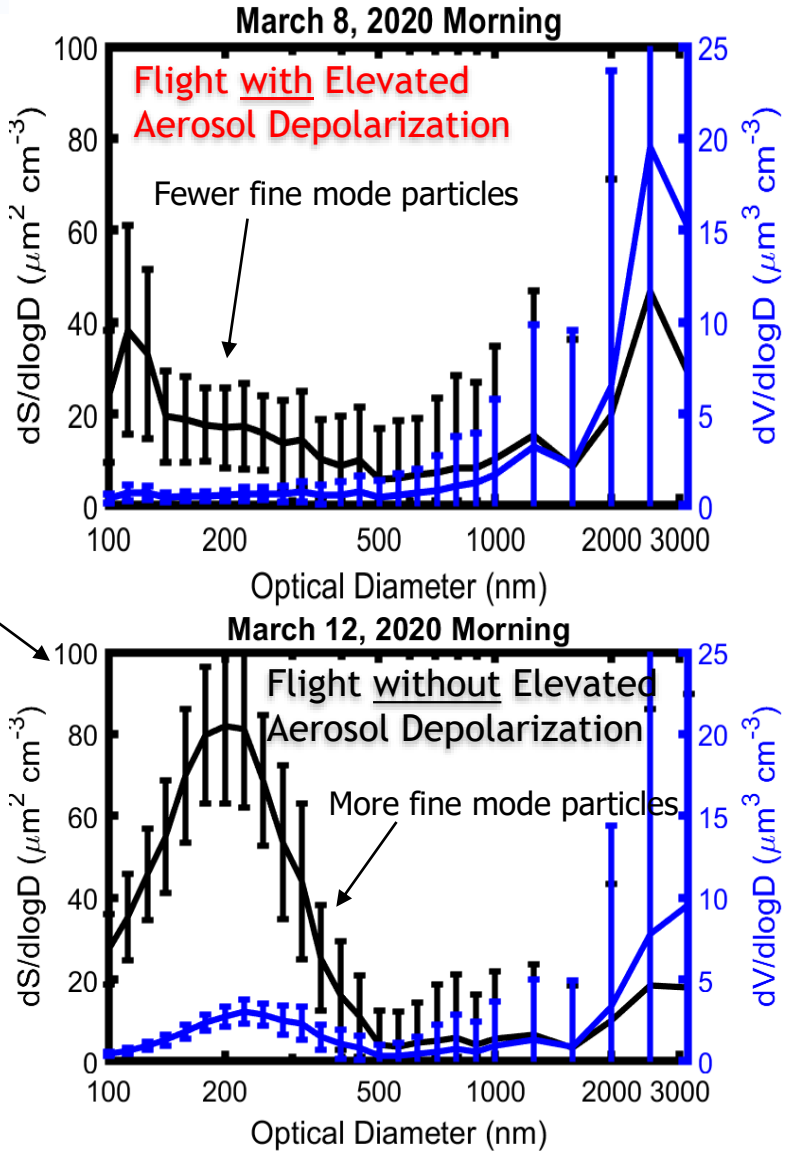


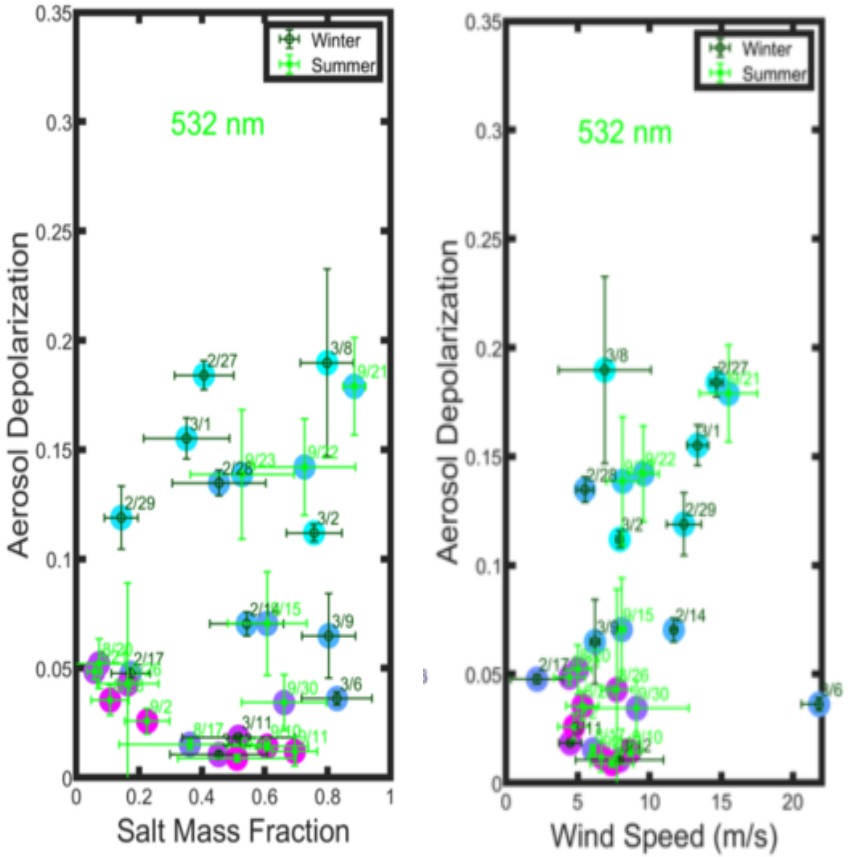




Airborne In situ Aerosol Size Distribution Measurements Show Fewer Fine Mode Particles When Enhanced Depolarization was Observed

- During March 8 flights (enhanced depolarization) airborne in situ aerosol size distribution measurements show a relative lack of fine mode particles.
- In contrast, during flights on March 12 (low depolarization), airborne in situ aerosol size distribution measurements show considerably more fine mode particles.
- During March 8 flights, airborne in situ aerosol size distributions were very similar at the bottom (where high depolarization was measured) and at the top (where low depolarization was measured) of the mixed layer - this suggests particle shape, not dry size, varied with RH





Elevated depolarization was not correlated with salt mass fraction or wind speed

Impact on CALIOP Operational Retrievals of Aerosol Optical Depth and Aerosol Backscatter and Extinction Profiles

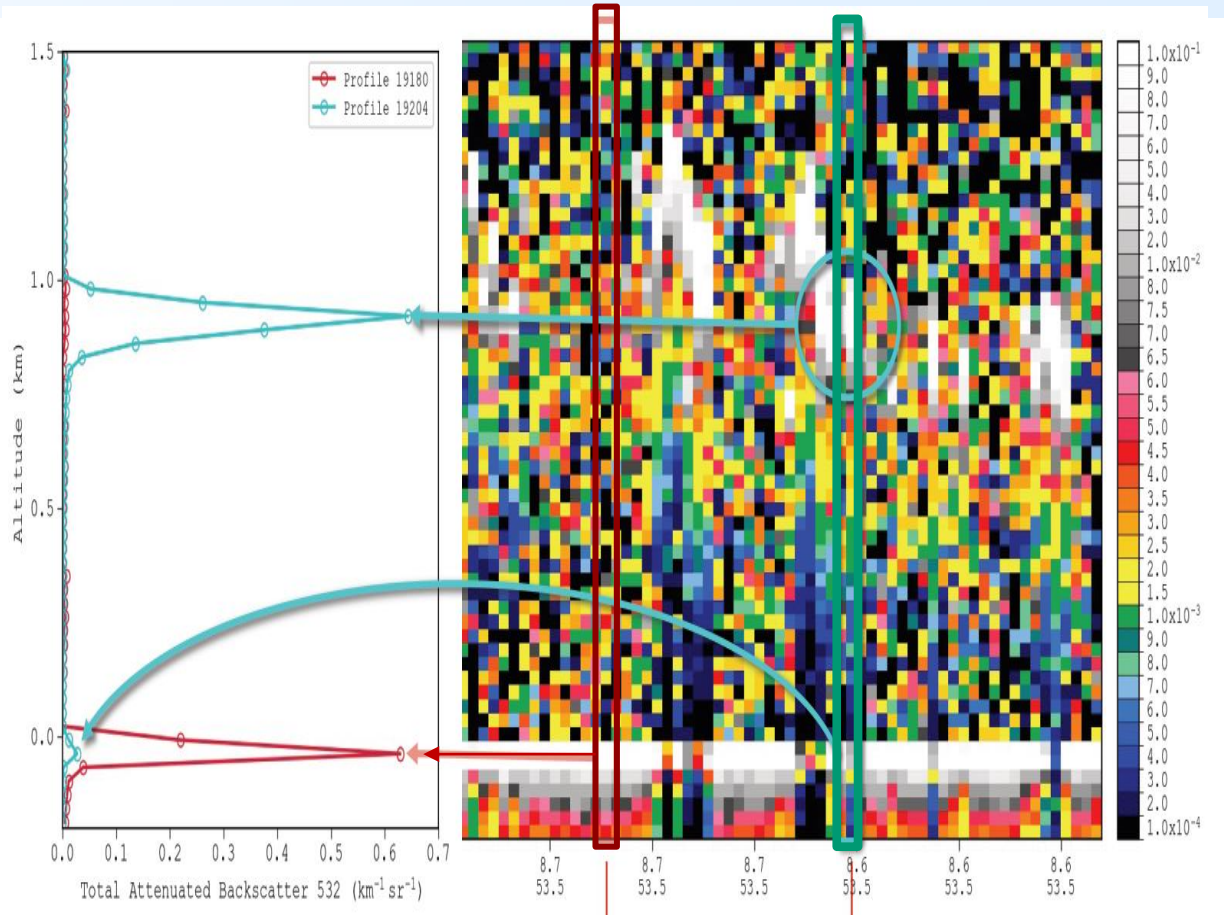
- Operational Methodology
  - Typically rely on identifying aerosol layers and specifying the aerosol extinction/backscatter ("lidar") ratio for these layers
  - Use location, altitude, integrated backscatter, depolarization to infer a specific aerosol type which is then assigned a specific lidar ratio
- Problems
  - Retrievals are limited to where aerosols are detected; background aerosol is not detected (Kim et al., 2016; Watson-Parris et al., 2018). The "missing" aerosols are significant so this leads to 30-50% underestimate in magnitude of aerosol direct radiative effects (Thorsen & Fu, 2015; Thorsen et al., 2017)
  - Inferred lidar aerosol types may be incorrect
  - Lidar ratios assigned to aerosol types may be incorrect
  - Actual lidar ratio distribution is usually continuous, not discrete
  - Lidar ratio uncertainties lead to uncertainties of 30% or more in derived AOD and extinction profiles

- Example: elevated depolarization associated with nonspherical sea salt
  - If CALIOP detects elevated depolarization, the aerosol is classified as dusty marine, polluted dust, or desert dust
  - The dusty marine, polluted dust, and desert dust have lidar ratios much greater than marine (37, 55, 44 vs. 23 at 532 nm) so misclassification of sea salt as dust will lead to significant high biases in aerosol backscatter, extinction, and (AOD)
  - Examination of CALIOP measurements during several Cold Air Outbreak episodes reveal that CALIOP also measured enhanced depolarization during such cases and that these typically also had low (<60%) RH.

Aerosol Subtype	Version 4 Lidar Ratio (sr)
Biomass Burning	70
Clean Continental	53
Clean Marine	23
Dust	44
Dusty Marine	37
Polluted Continental	70
Polluted Dust	55

New Alternative Method: CALIOP Retrieval of Aerosol Extinction Profiles using Ocean Derived Column Optical Depths (OD-COD)

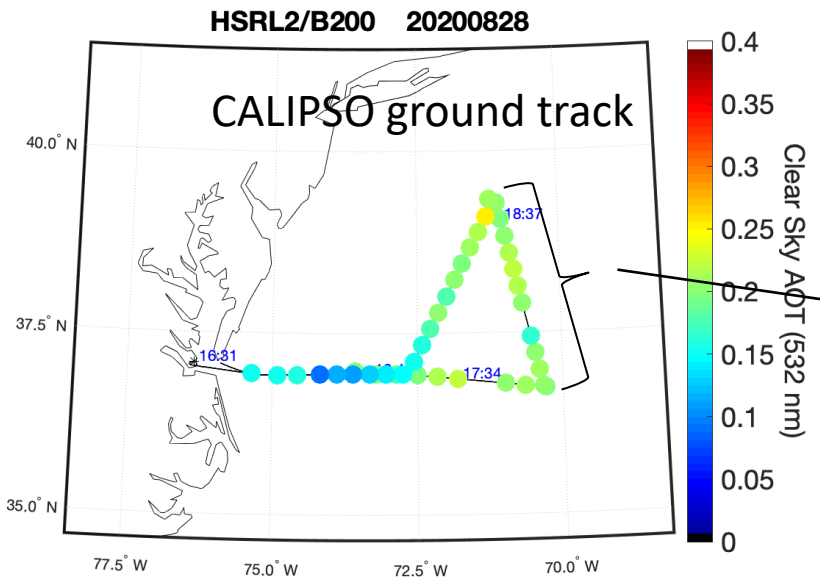
- Method
  - Use the ocean surface return signal to derive the attenuation caused by overlying aerosols and/or clouds
  - Two-way transmittance is derived from the ocean surface return signal and the ocean surface retro reflectance which depends on wind speed (from MERRA-2 model)
  - Optical depth is calculated from two-way transmittance
  - Aerosol Extinction profiles are computed using the Optical Depth Constraint

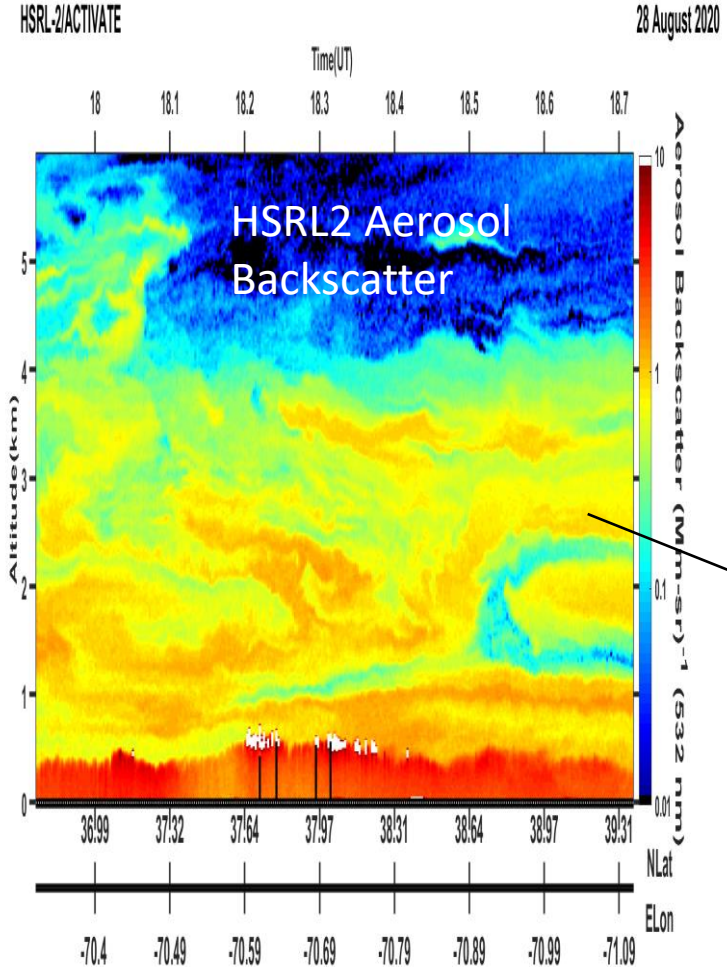


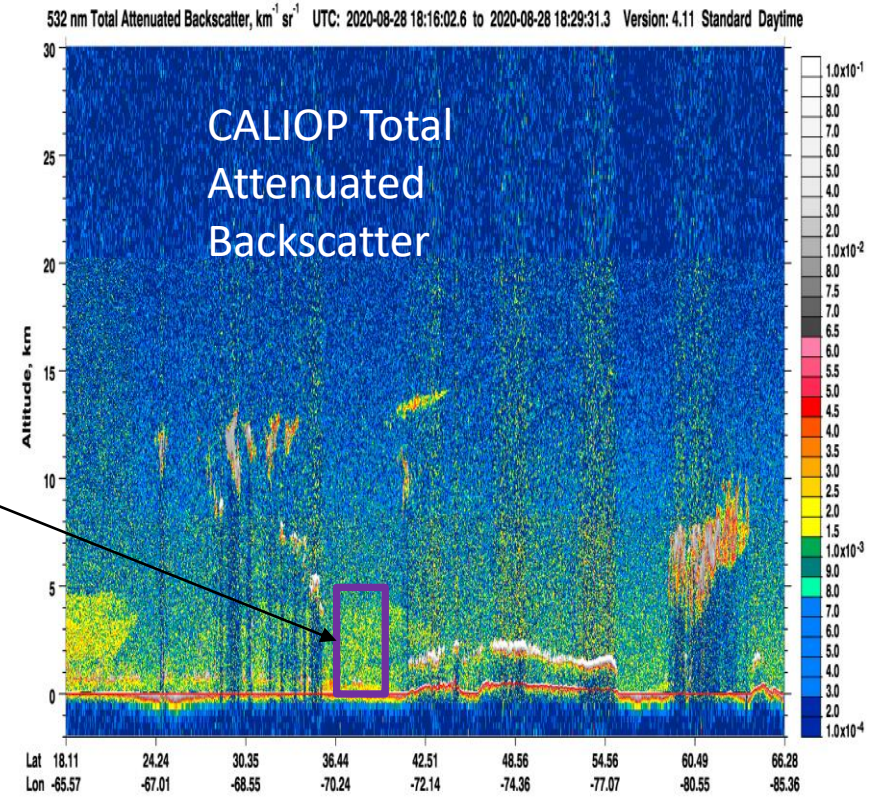
Venkata, S. and Reagan, J.: Aerosol Retrievals from CALIPSO Lidar Ocean Surface Returns Remote Sens., 8, 1006, https://doi.org/10.3390/rs8121006, 2016.

Comparison with HSRL-2 measurements – ACTIVATE Aug. 28, 2020

- Preliminary evaluation using HSRL-2 measurements acquired during ACTIVATE flight on Aug. 28, 2020

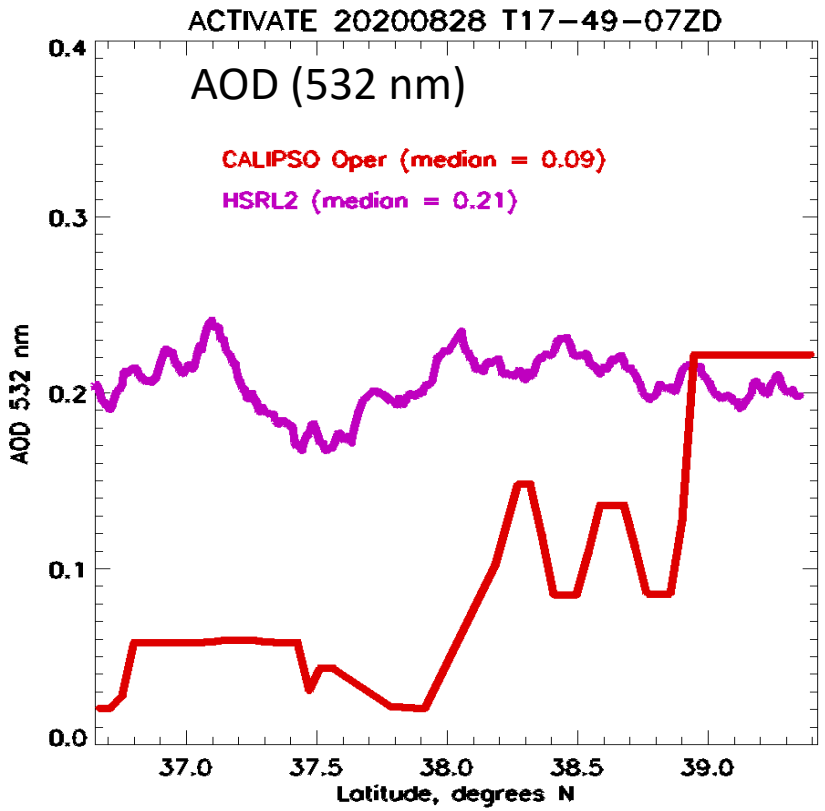


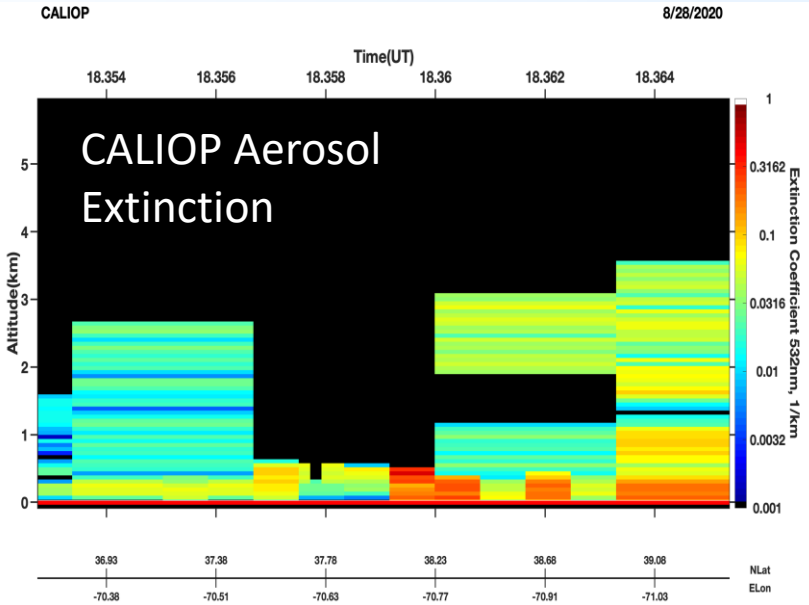


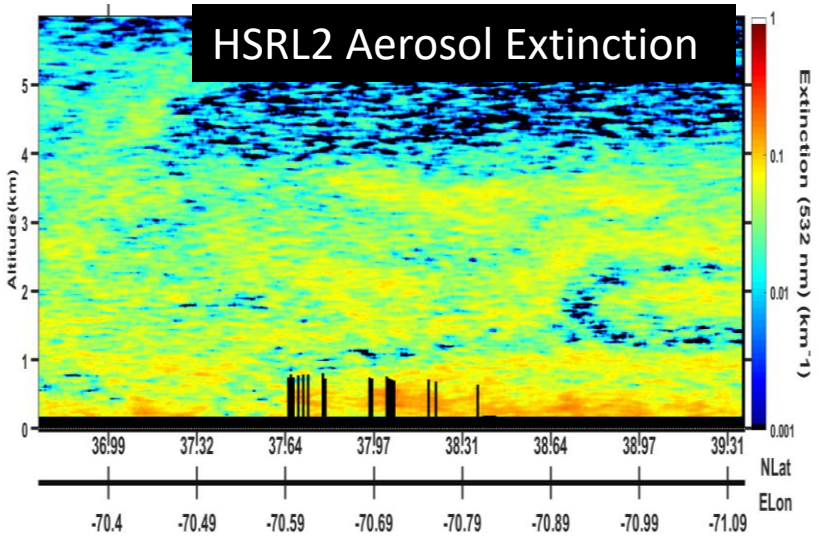


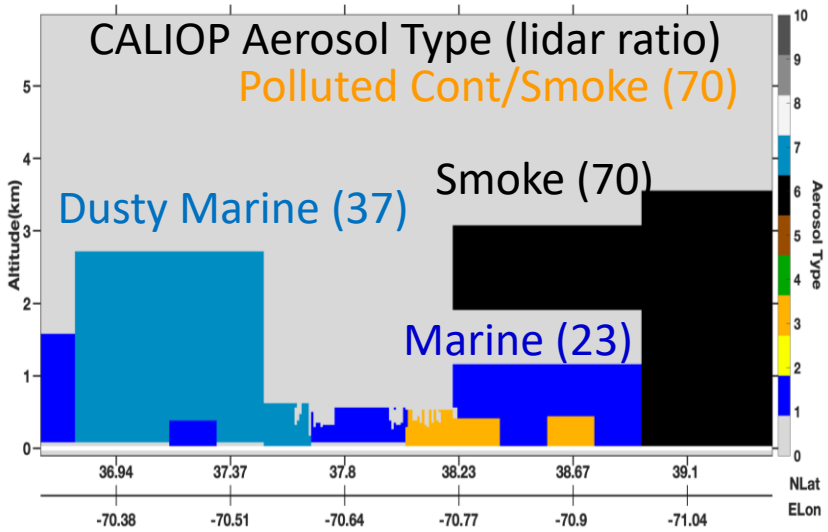
CALIOP Standard Aerosol Retrieval on August 28, 2020

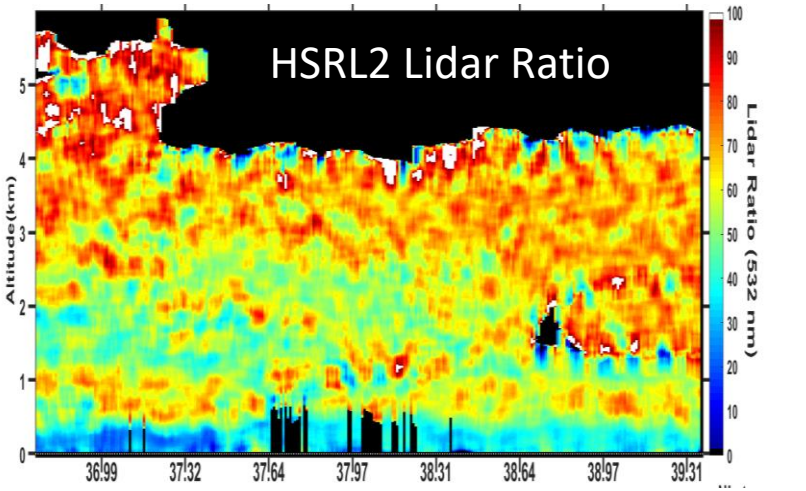
- Standard CALIOP AOD retrieval generally lower than HSRL2 AOD due to aerosol misclassification leading to low lidar ratios
- Better agreement at end of record where CALIOP identifies smoke through column



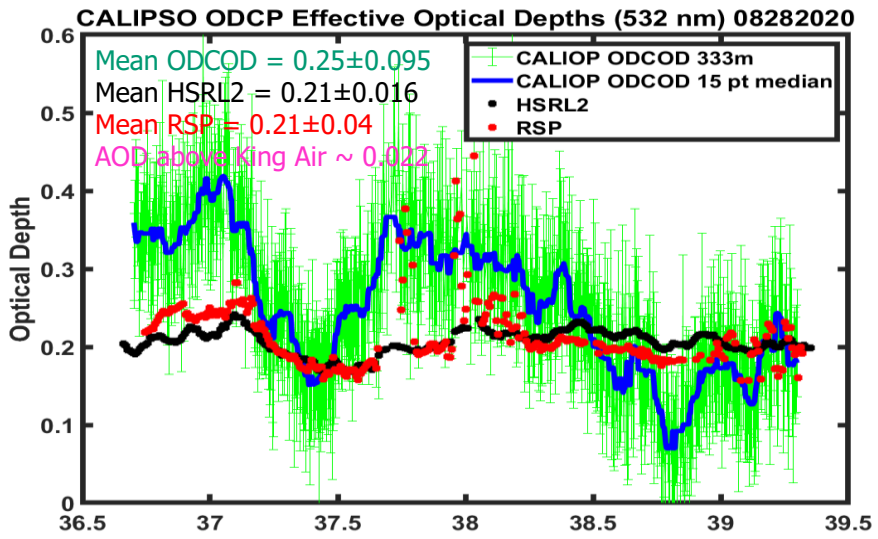


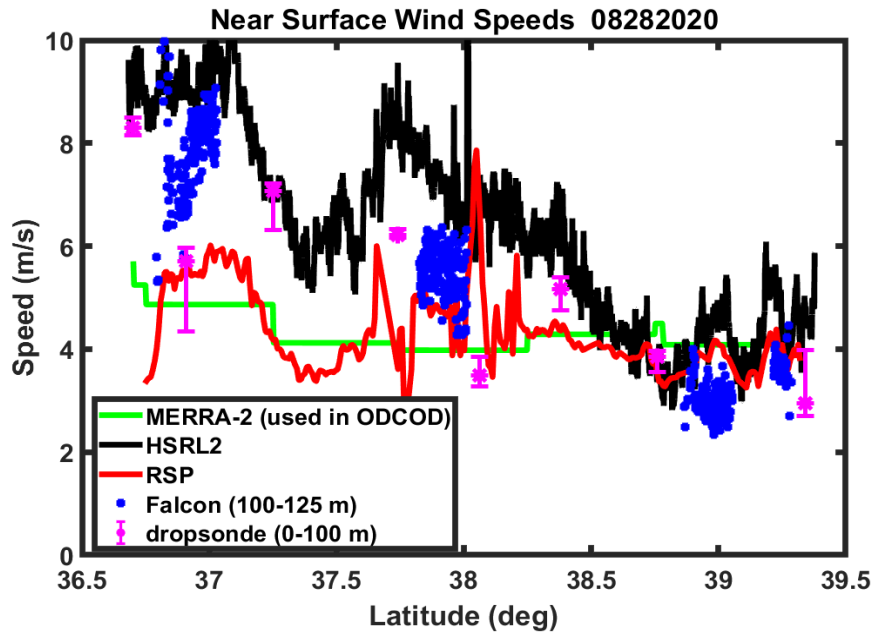




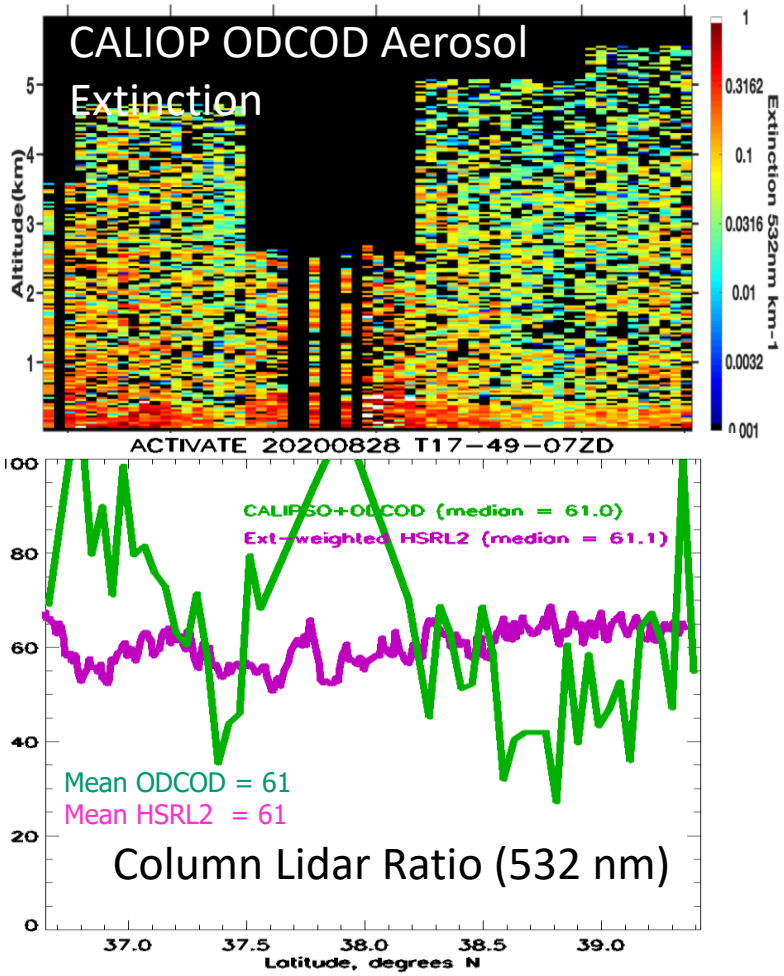


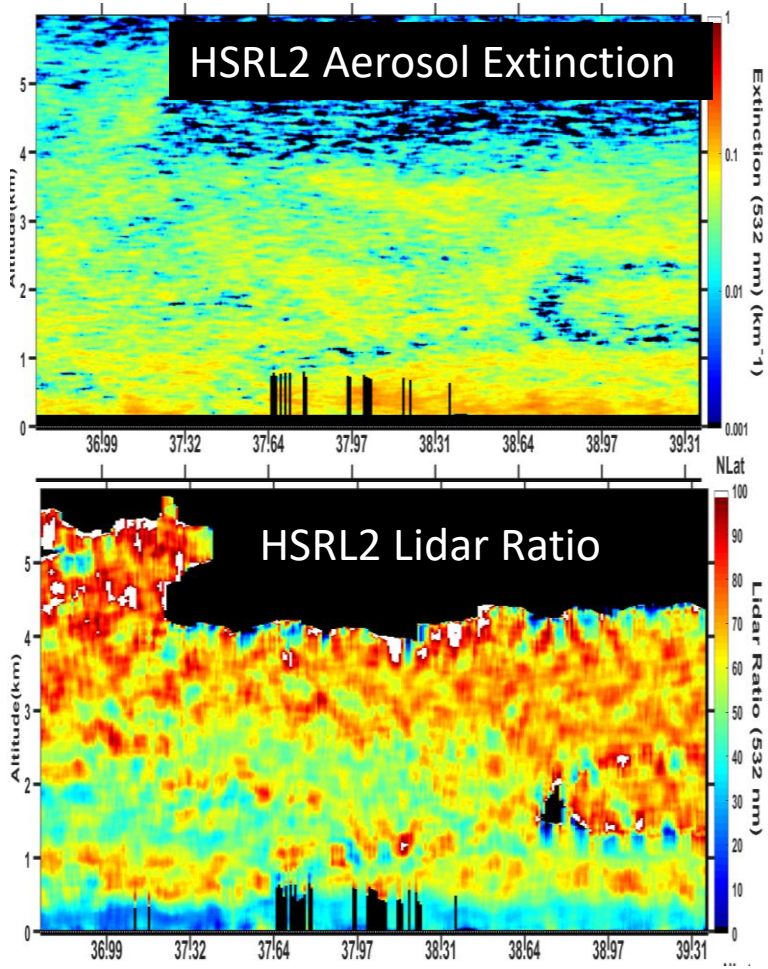
CALIOP ODCOD Aerosol Retrieval on August 28, 2020 (Preliminary)



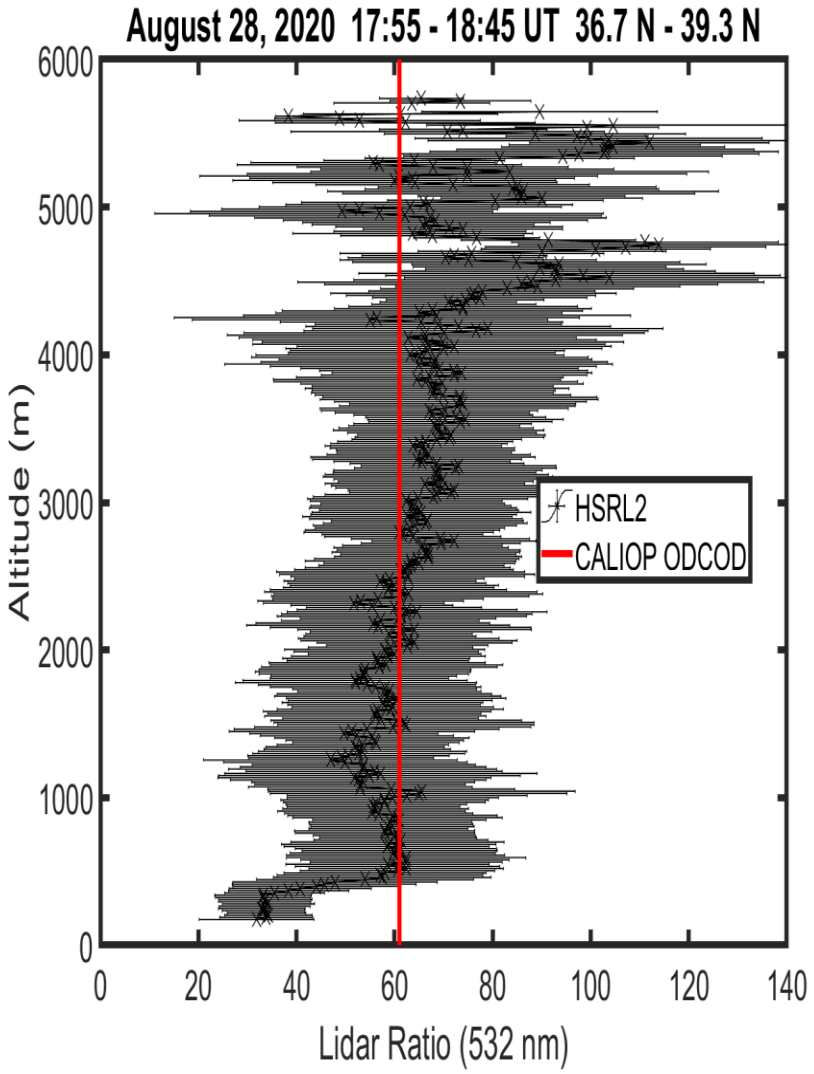


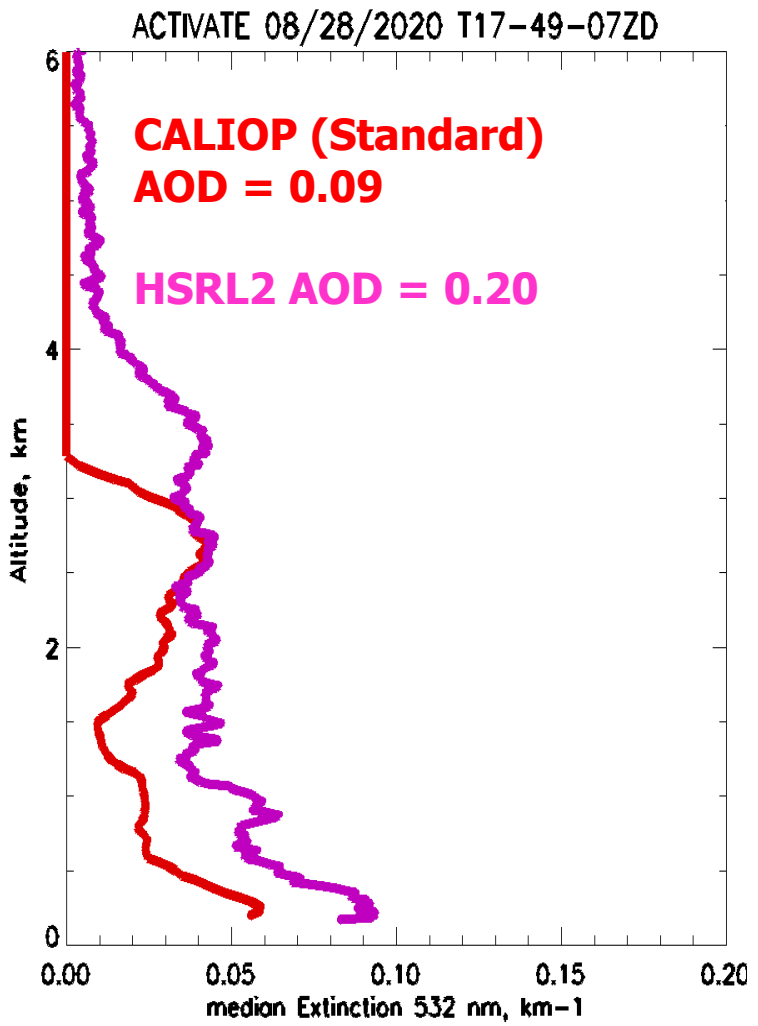
- ODCOD mean AOD and Lidar Ratio in much better agreement with HSRL2 and RSP
- Differences are likely to due uncertainty in MERRA-2 near surface wind speeds
- Sanja Dmitrovic (U of A) examining wind speed comparisons in more detail

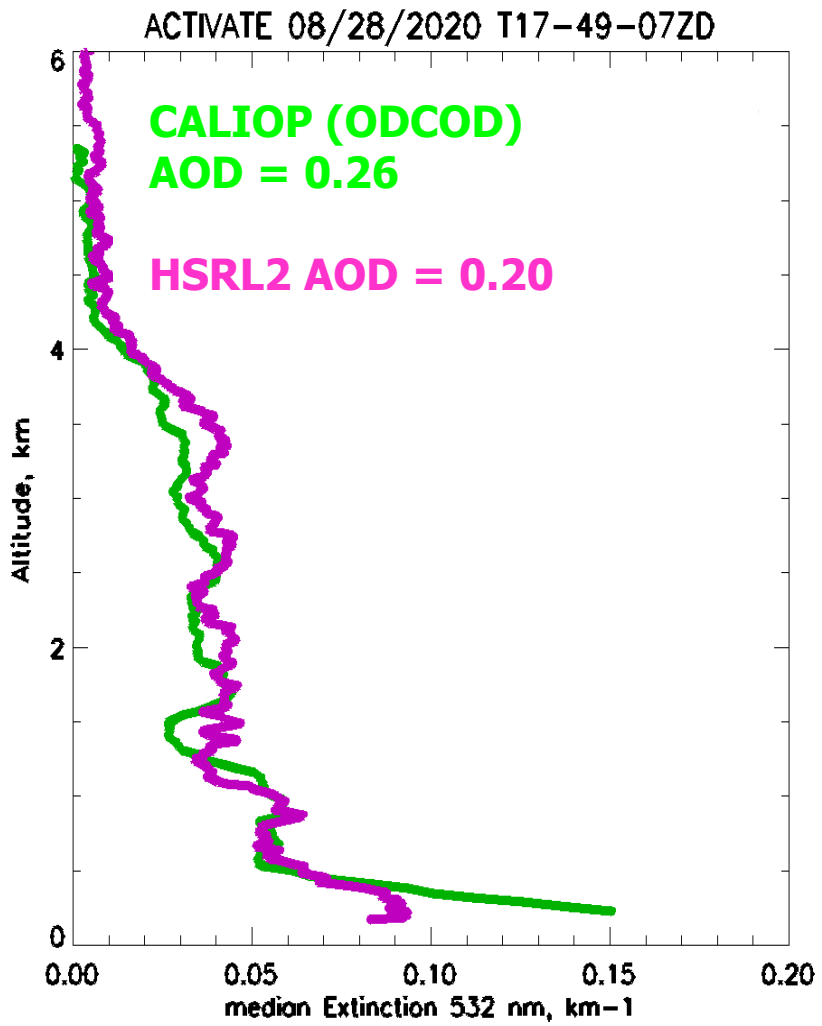




CALIOP (Standard and ODCOD) and HSRL2 Median Vertical Aerosol Extinction Profiles (Preliminary)

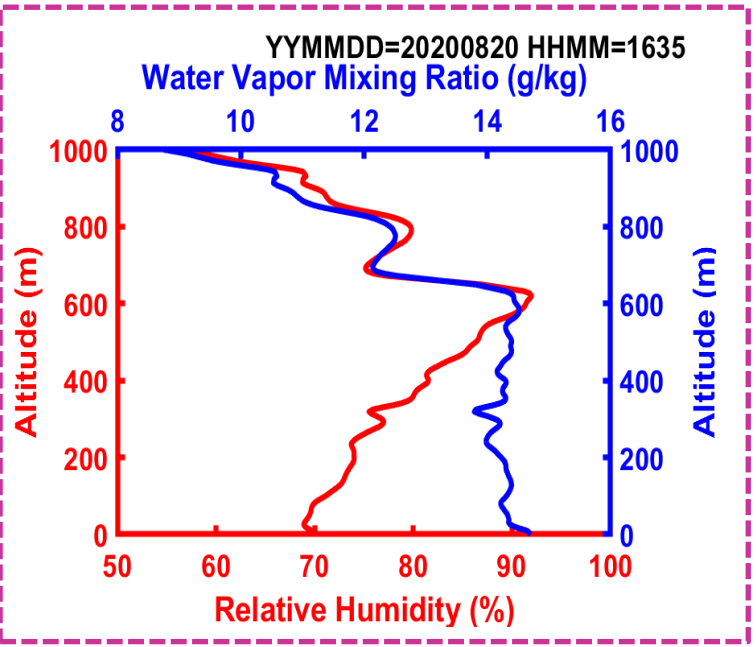


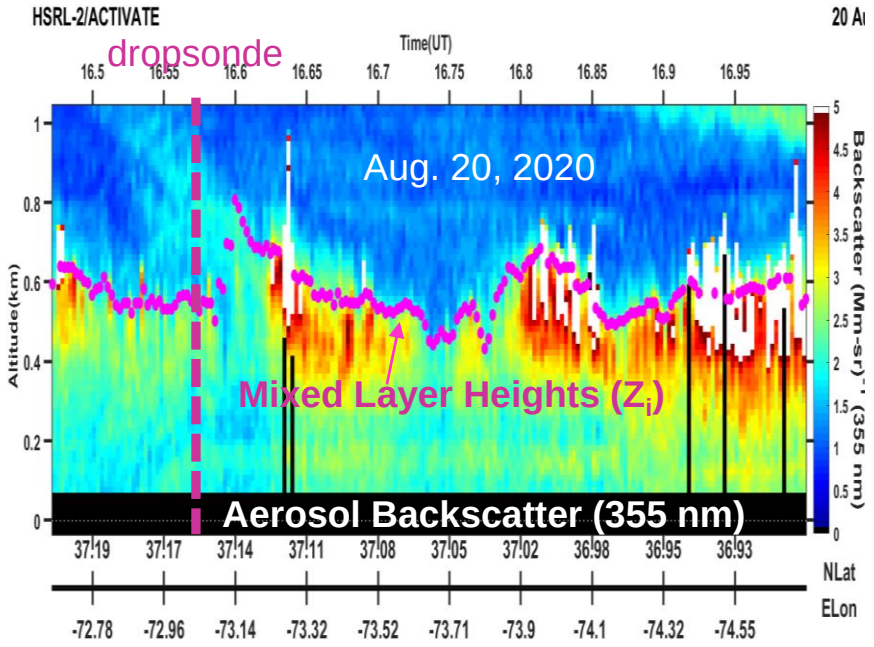


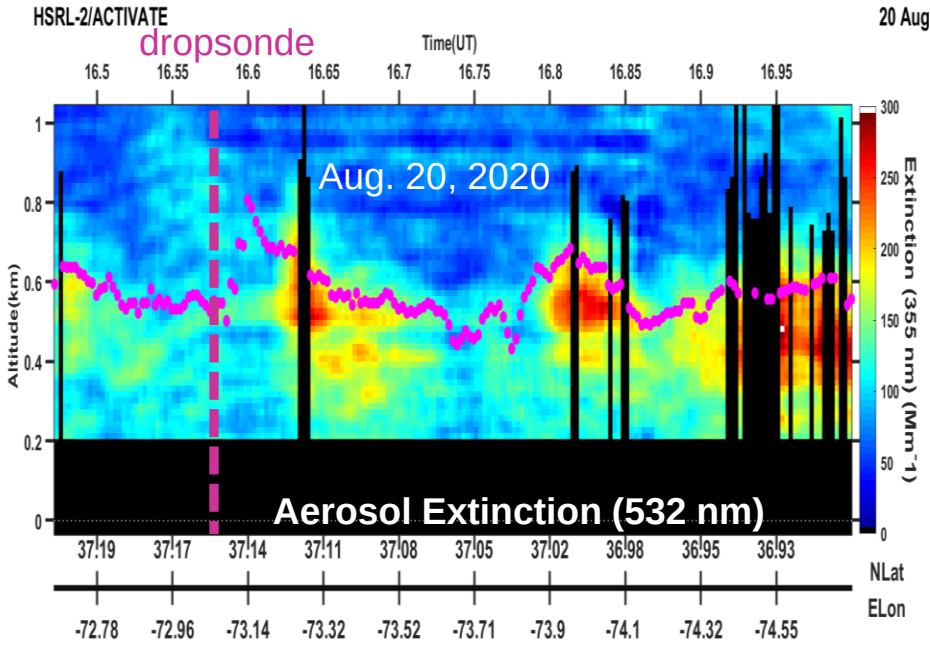


Aerosol Backscatter and Extinction Increase with Height in Mixed Layer associated with Increase in Relative Humidity (RH)

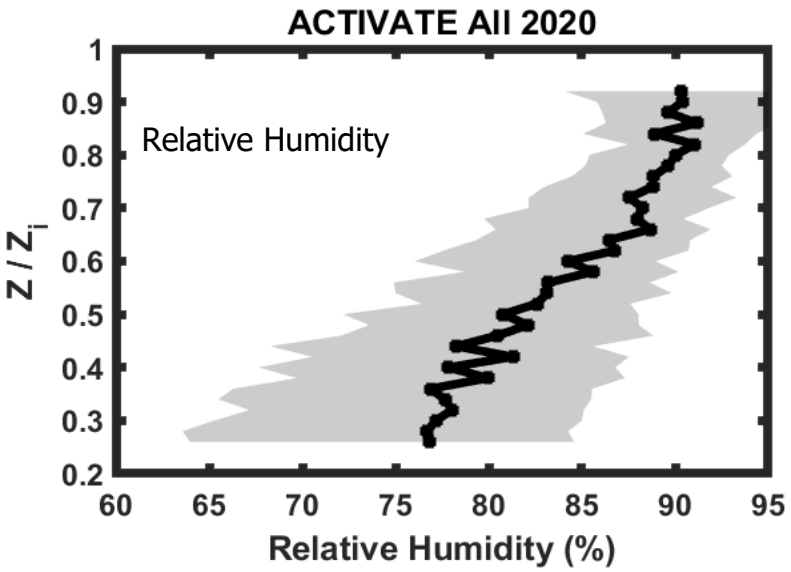
- Dropsondes provide relative humidity profiles
- Mixed Layer Height (Z_i) derived from HSRL2 aerosol backscatter profiles
- Nearly constant water vapor mixing ratio (conservative tracer) to reduce changes due to changes in air mass
- Changes in RH due to changes in temperature
- As RH increases with height within Mixed Layer, fine mode hygroscopic particles take on water, so aerosol backscatter and extinction increase.

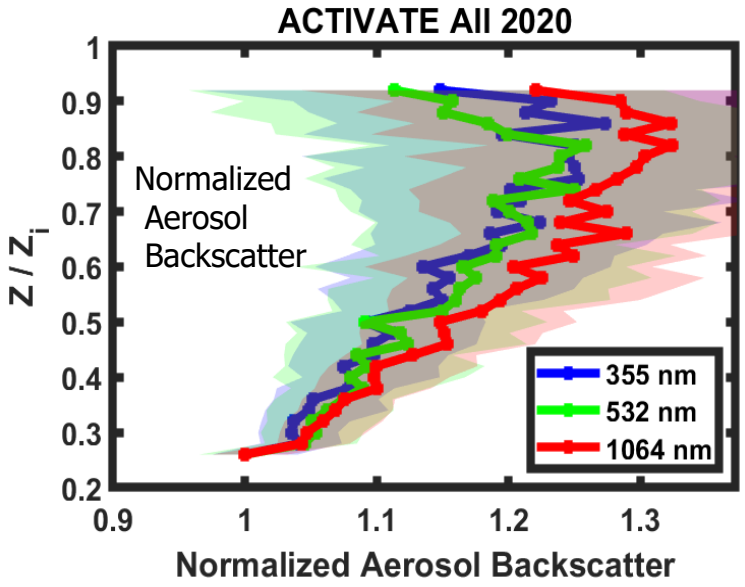






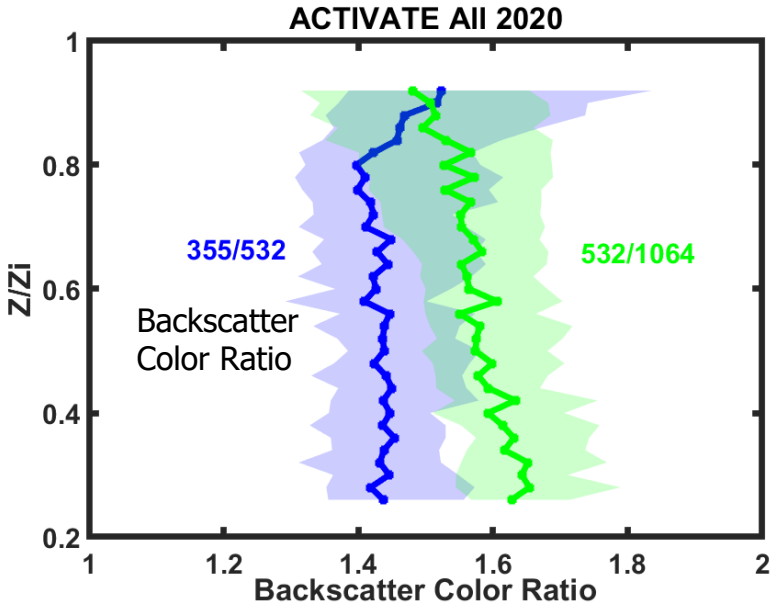
ACTIVATE: Aerosol Backscatter and Extinction Increase with Height in Mixed Layer associated with Increase in Relative Humidity (RH)

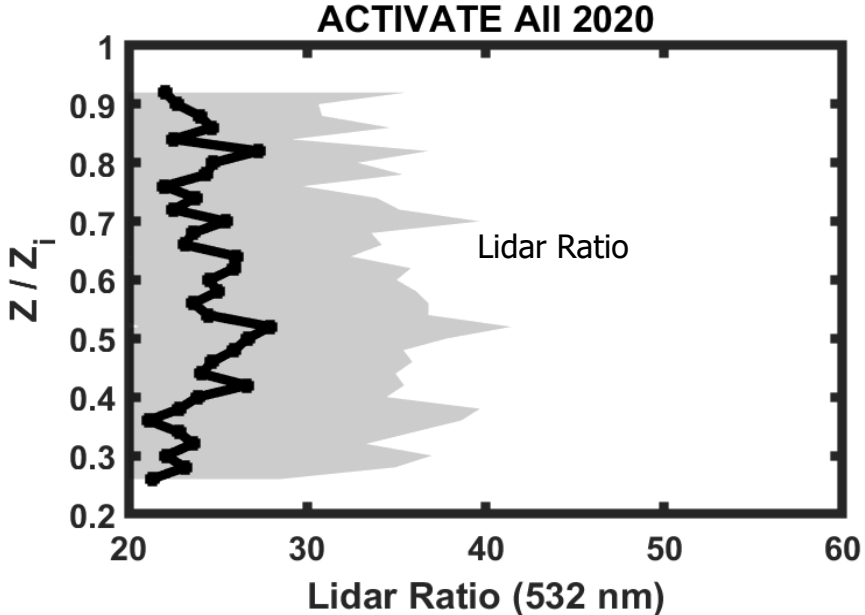


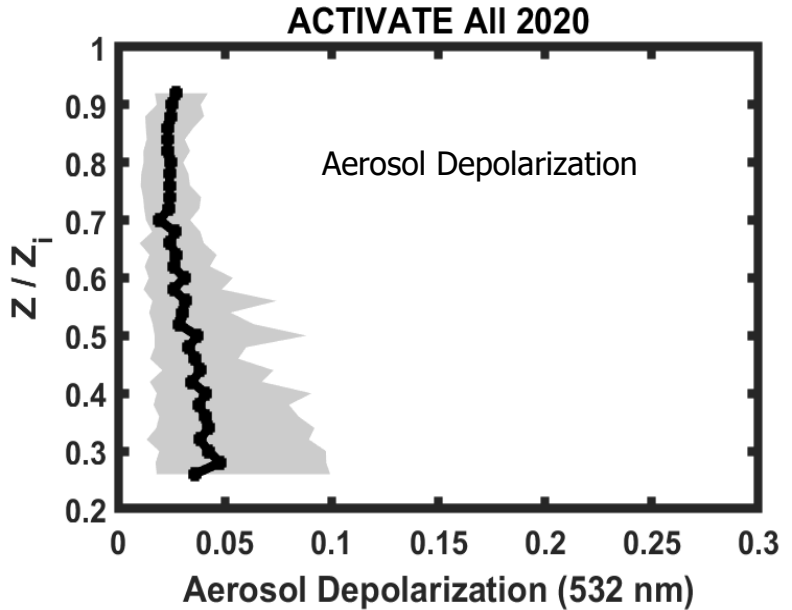


Overall (on average)

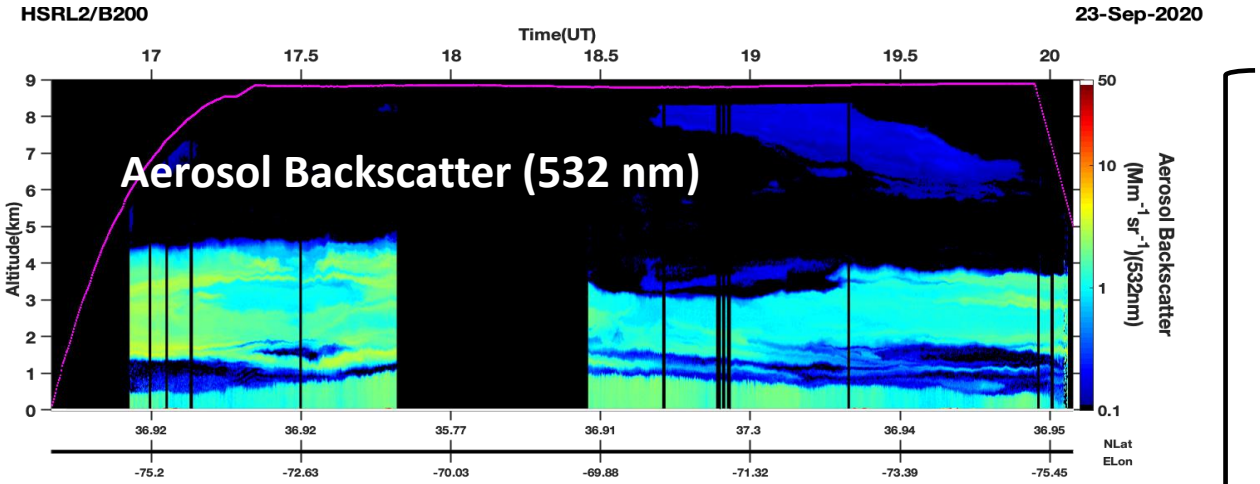
- Relatively small increases in aerosol backscatter and extinction with increased RH
- Little change in color ratios, lidar ratio, and aerosol depolarization ratio with RH suggest relatively little change in size and shape



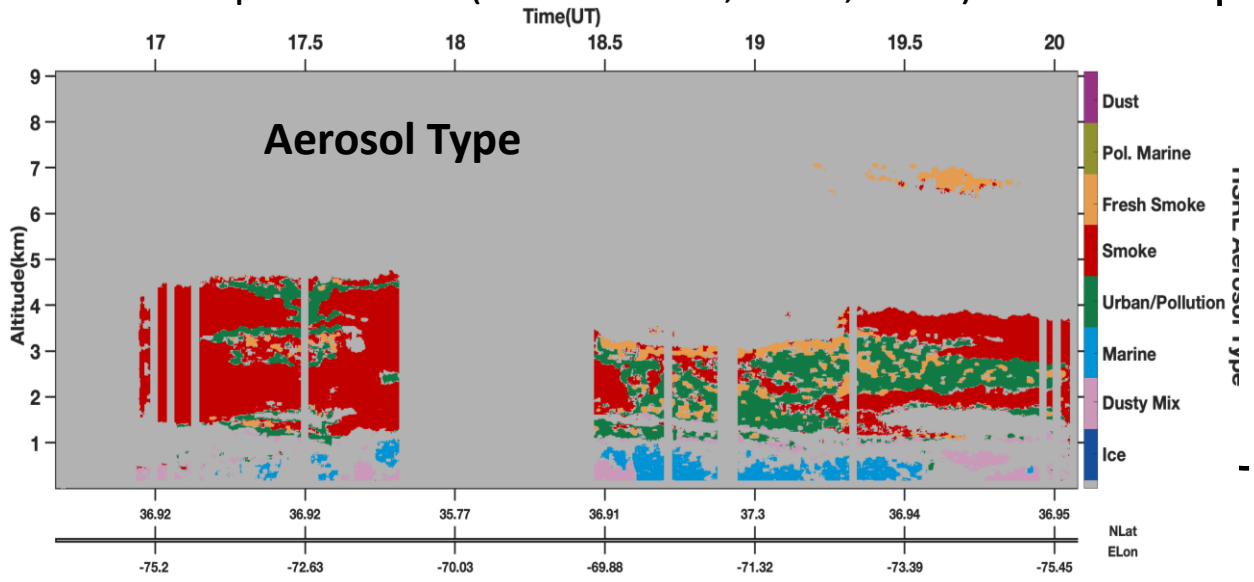


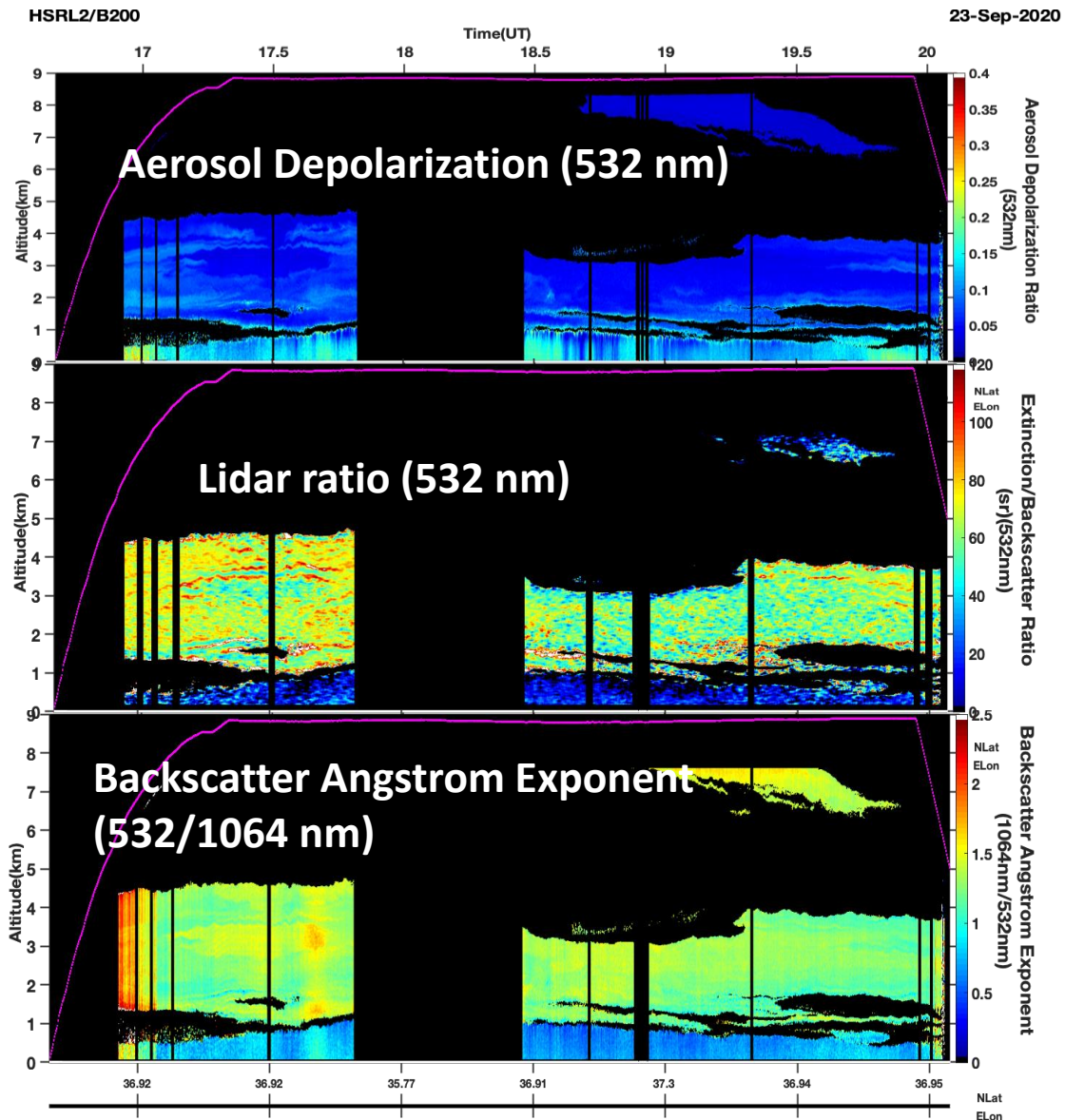


HSRL2 Measurements used to Infer Aerosol Type



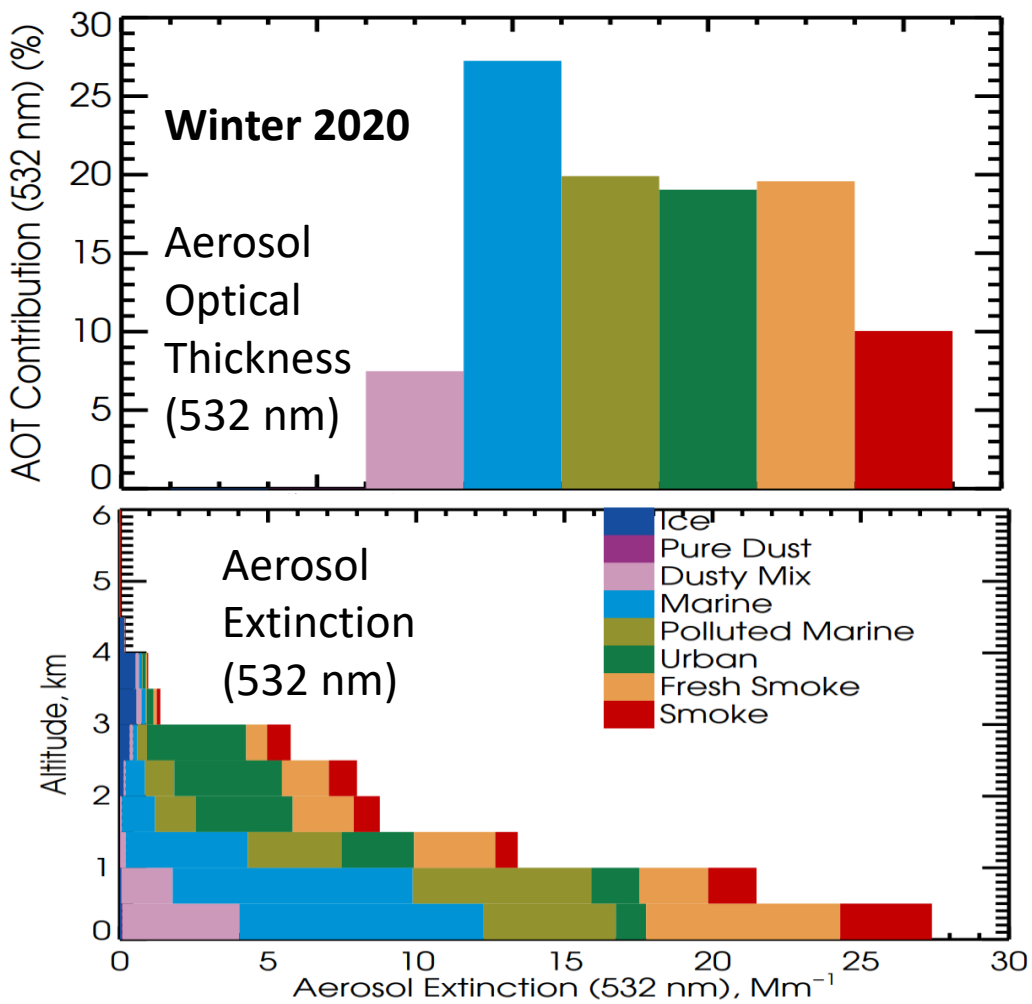
Aerosol type inferred from measurements of aerosol intensive parameters (Burton et al., 2012, AMT)

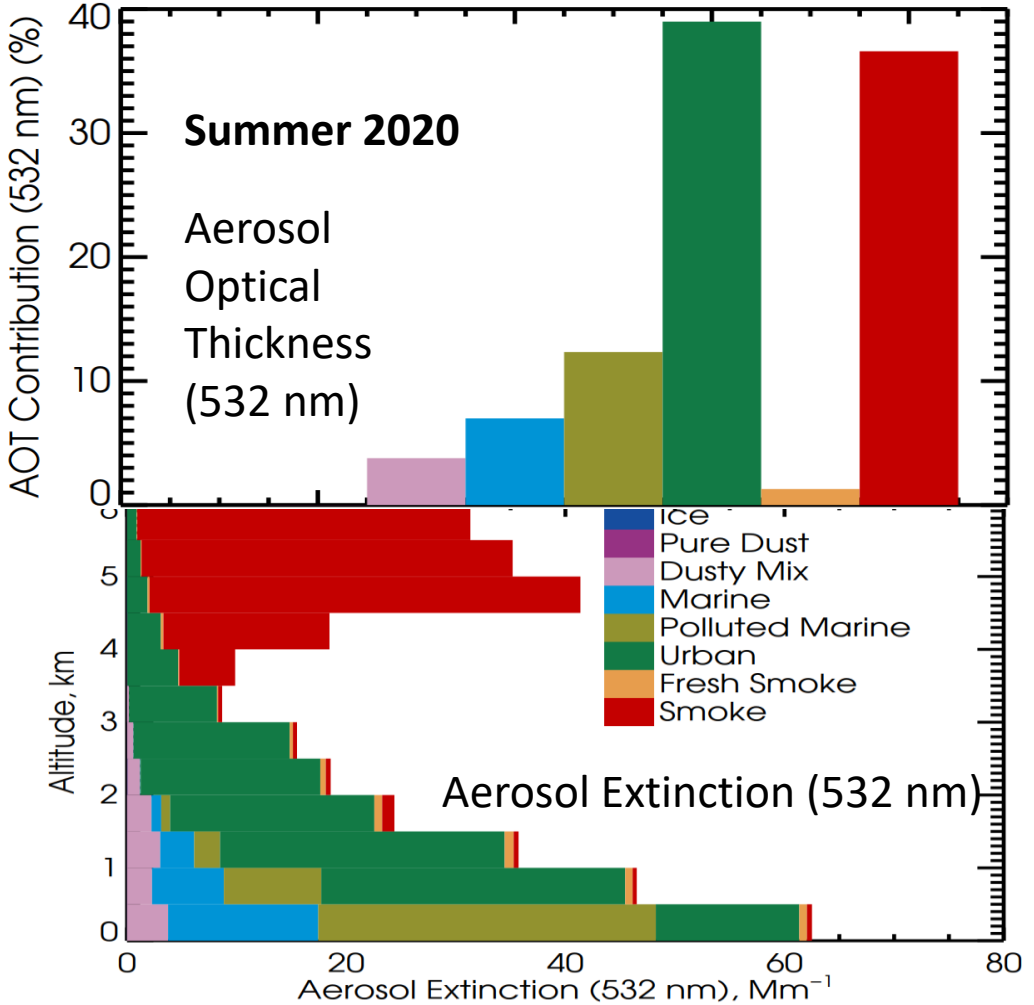




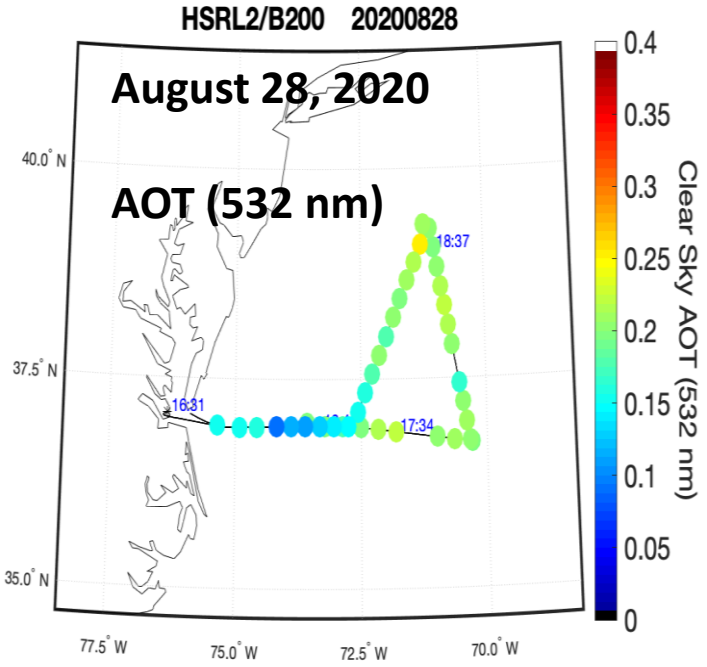
AOT and Aerosol Extinction Apportioned to Aerosol Type

- Larger contribution of sea salt to AOT and extinction in the winter
- Larger contribution of smoke to AOT and extinction in the summer



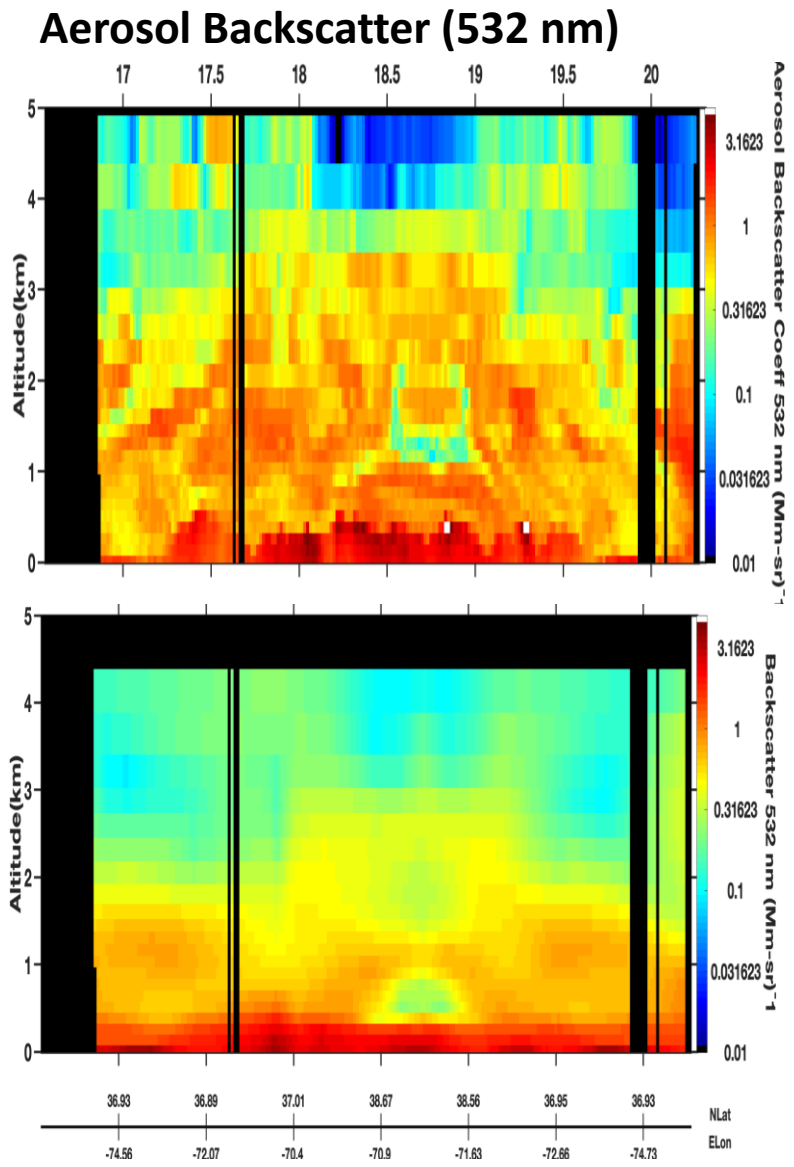


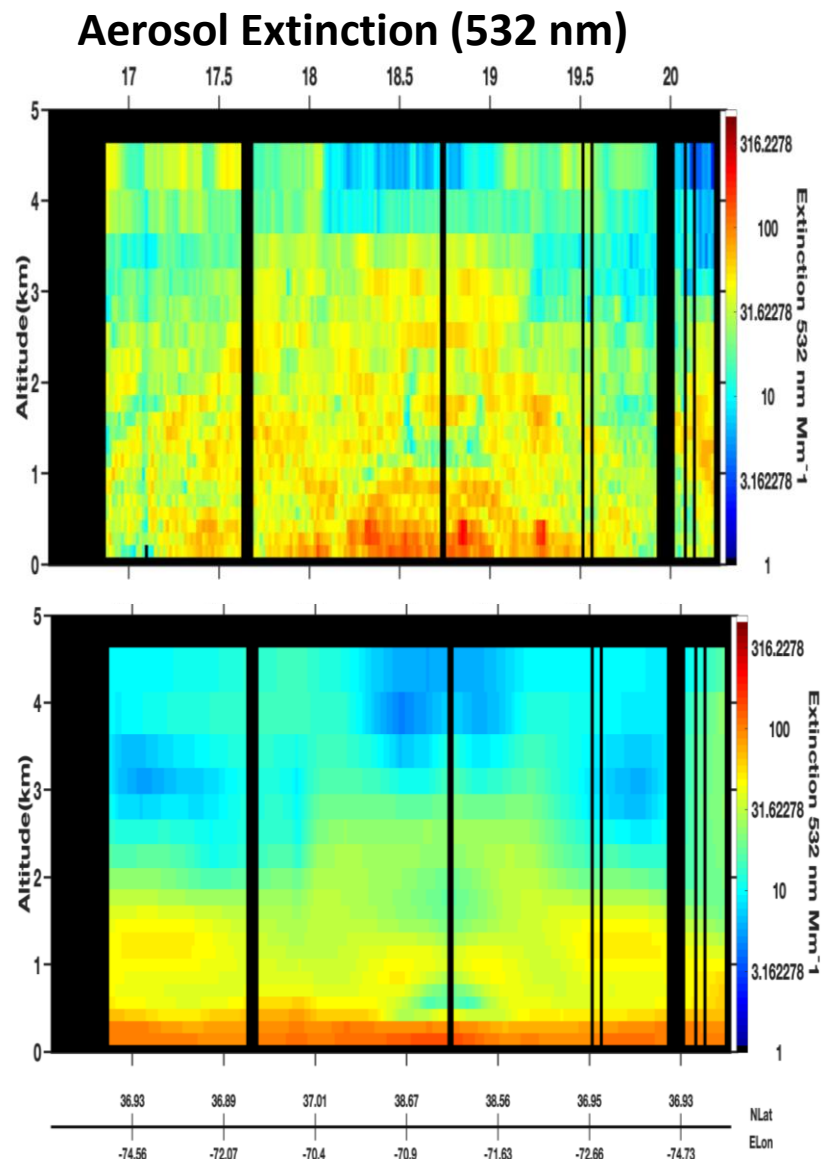
Example: HSRL-2/MERRA-2 Comparison of Aerosol Extensive Parameters for Aug. 28, 2020



HSRL2

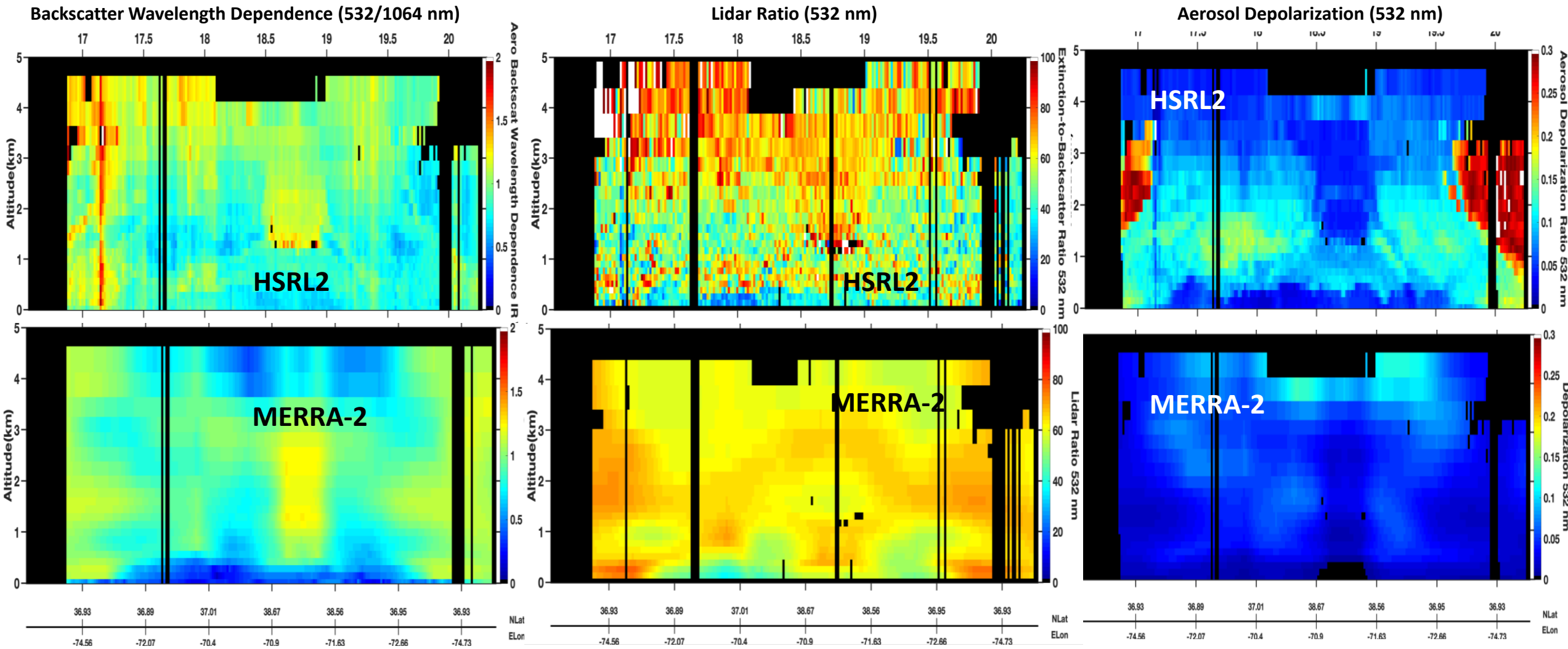
MERRA-2





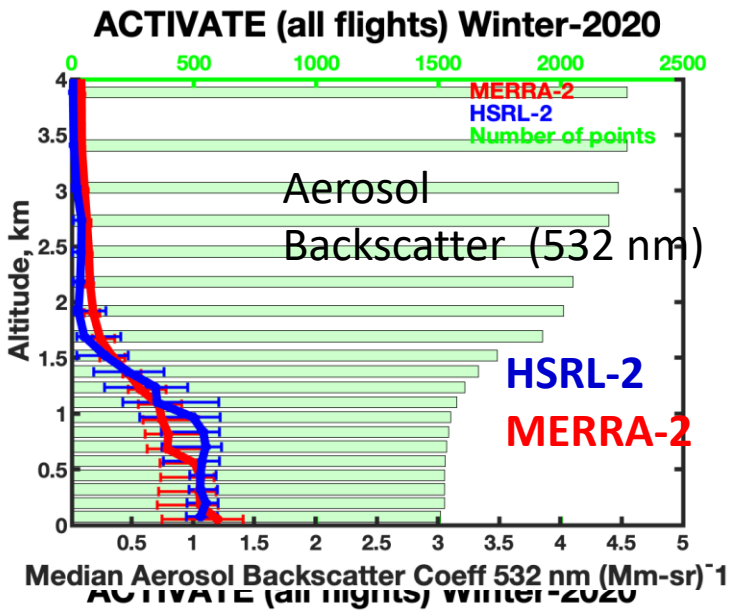
MERRA-2 Simulations provided by Arlindo da Silva (GSFC)

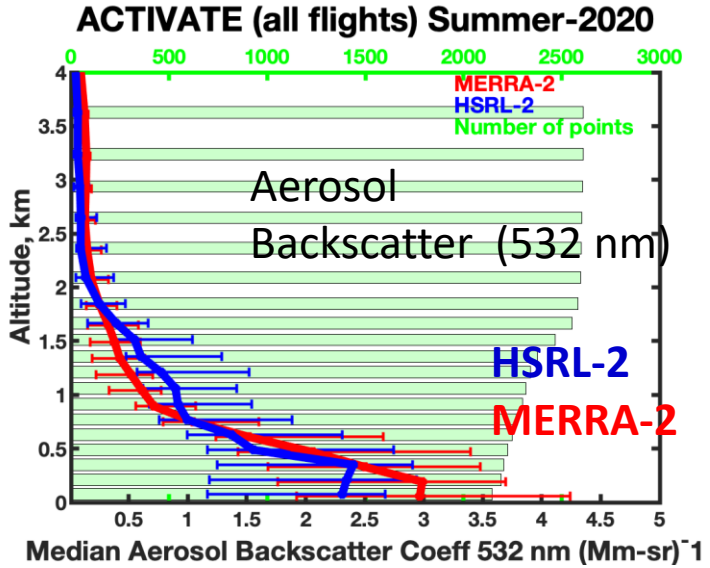
Example: HSRL-2/MERRA-2 Comparison of Aerosol Intensive Parameters for Aug. 28, 2020

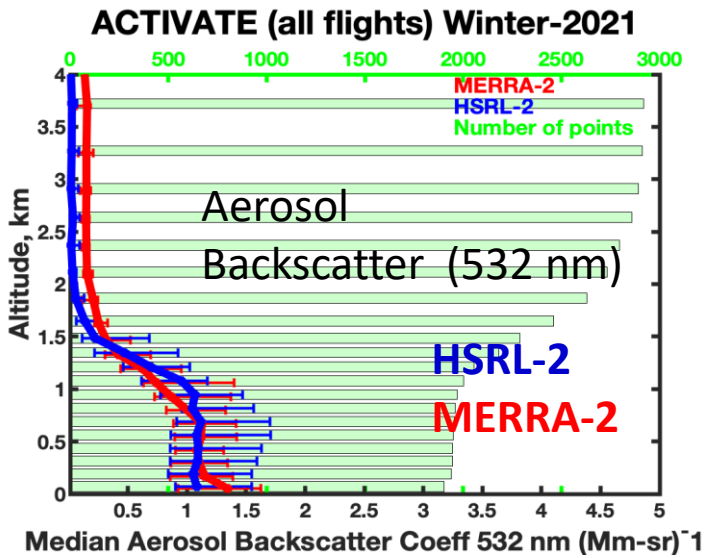


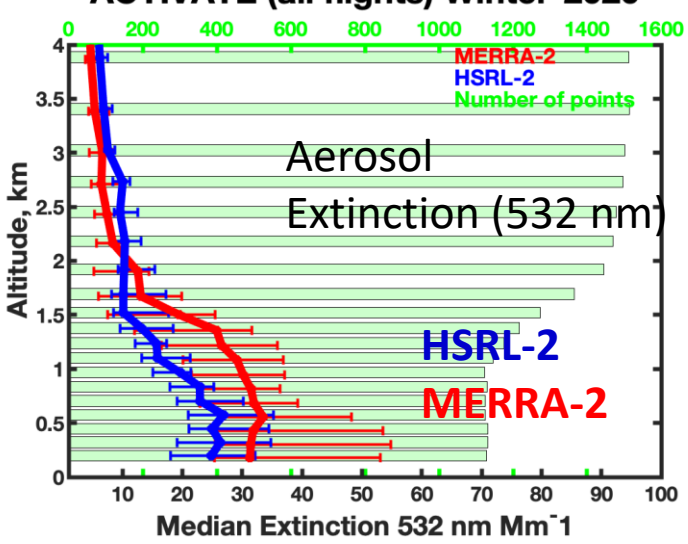
MERRA-2 Simulations provided by Arlindo da Silva (GSFC)

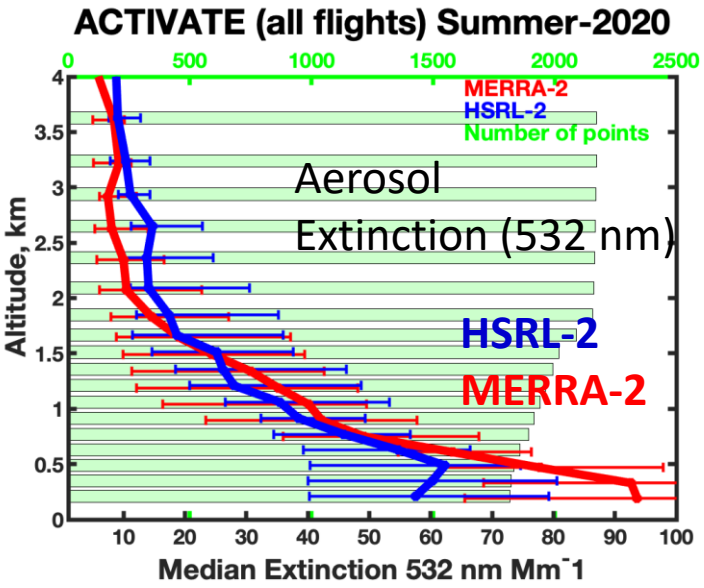
HSRL- 2/MERRA-2 Comparison of Median Aerosol Profiles for ACTIVATE Missions

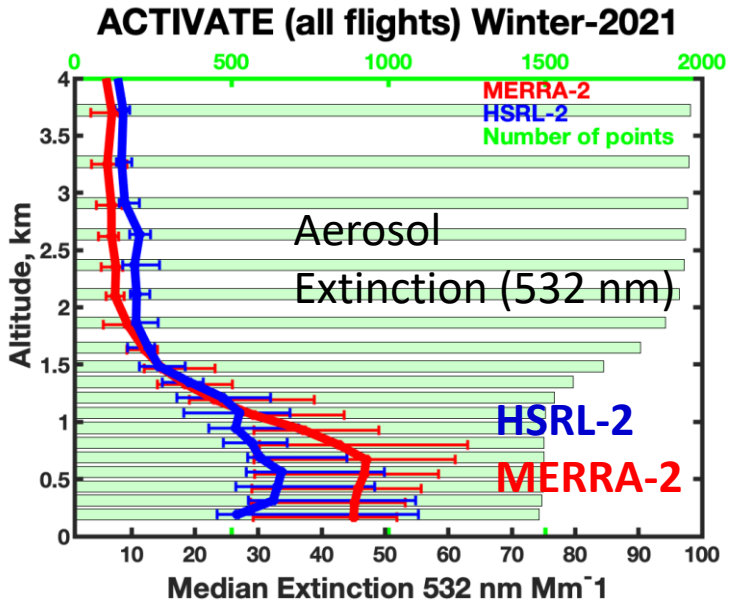




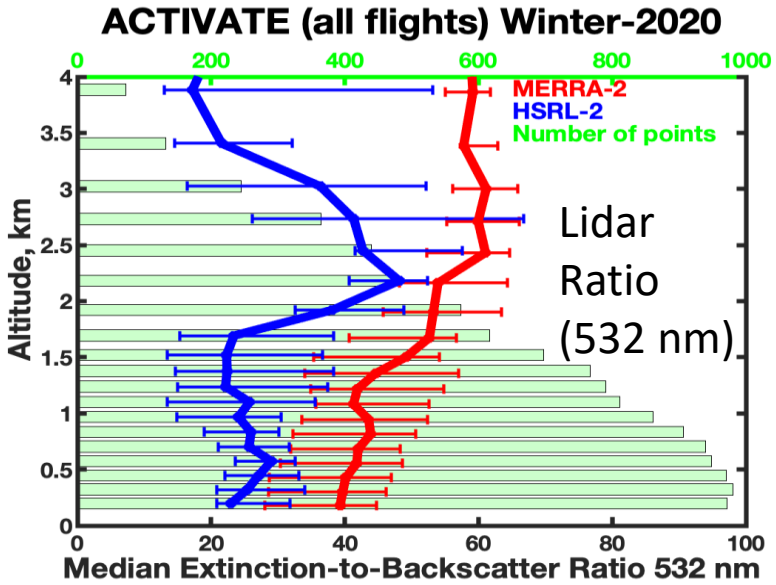


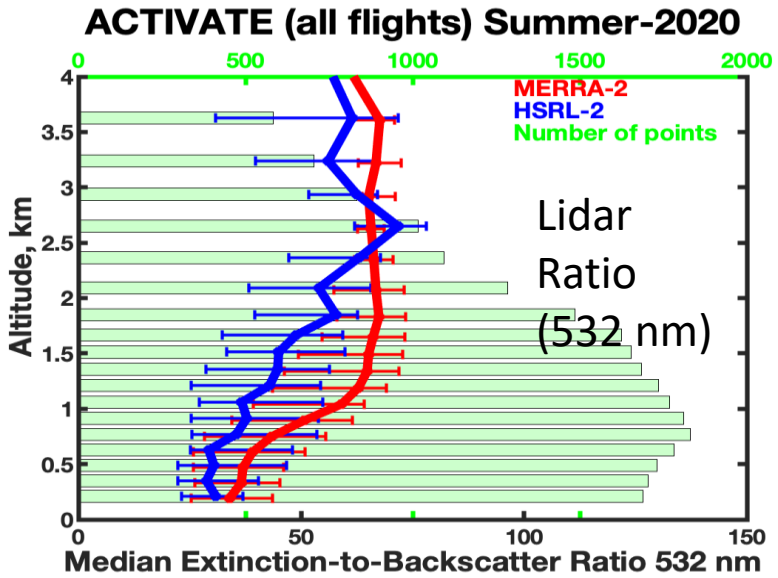


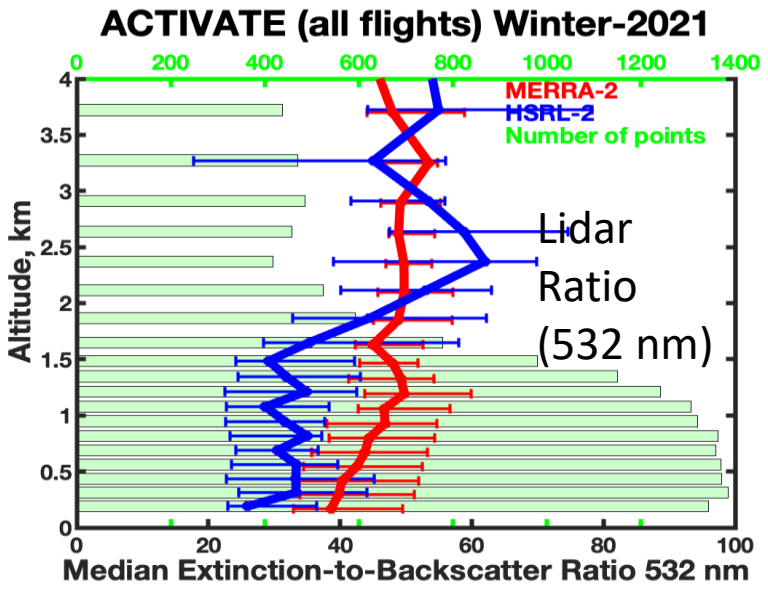


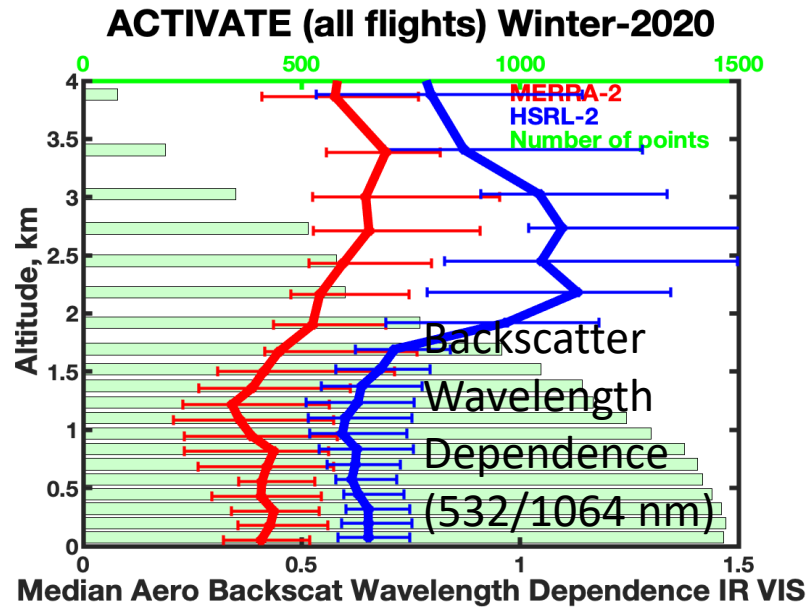


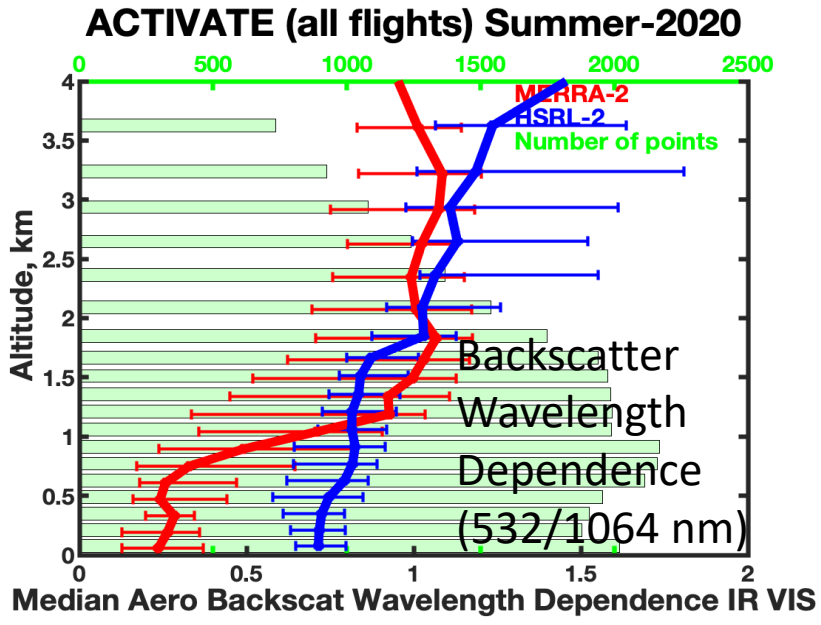
HSRL- 2/MERRA-2 Comparison of Median Aerosol Profiles for ACTIVATE Missions

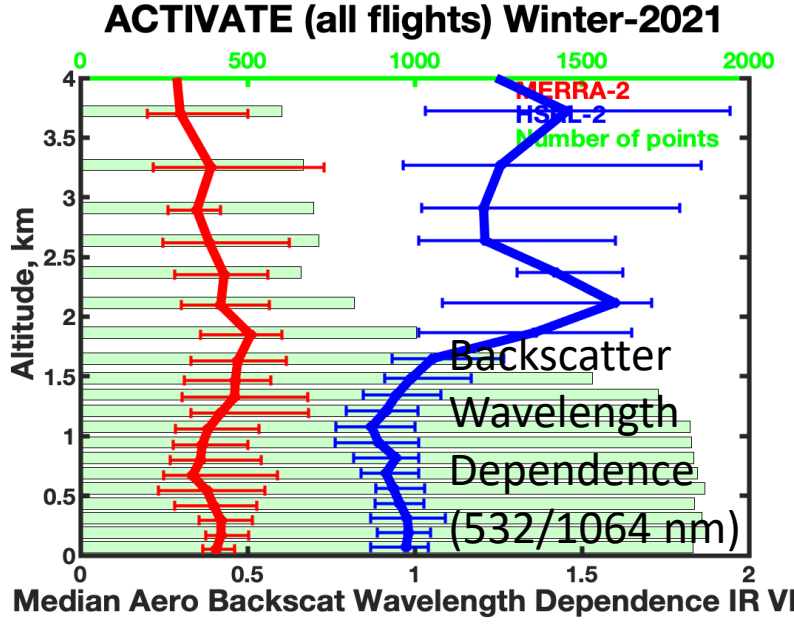








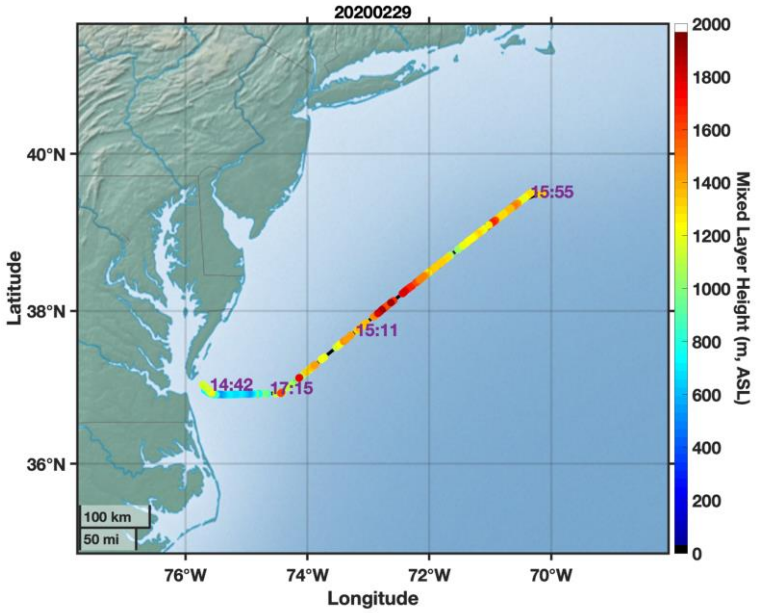


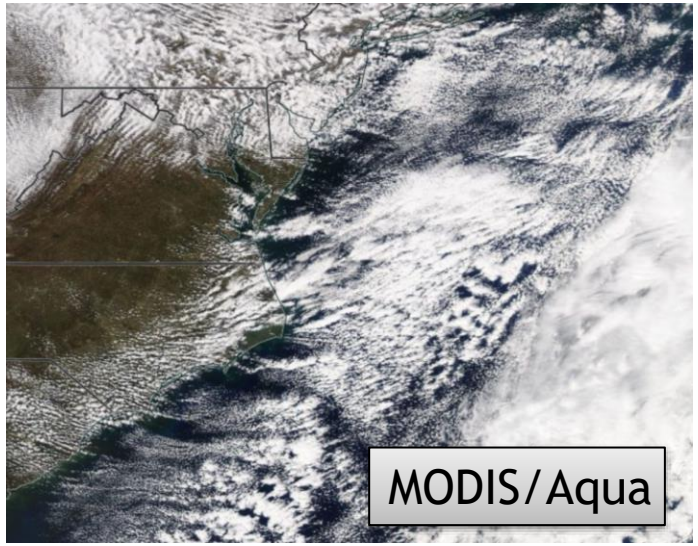


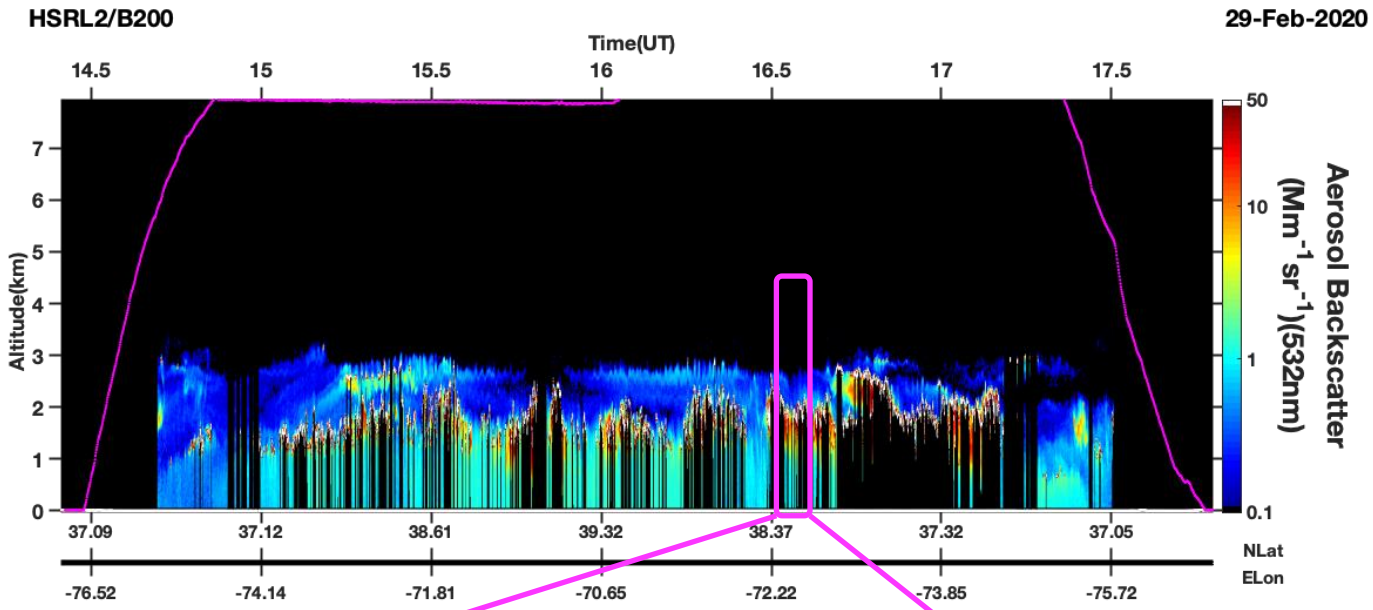
Lidar Cloud Measurement Summary

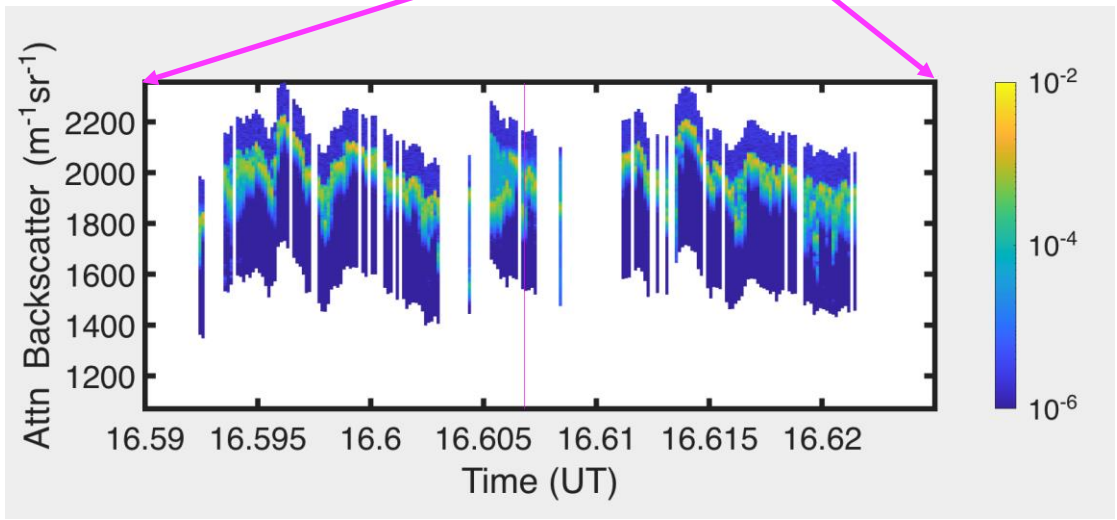
- **Cloud Top Height:** (1.25 m vertical resolution) based on backscatter gradient and absolute backscatter value
- **Cloud Top Extinction** (mean and profile) based on profile of integrated backscatter and depolarization following methods developed by Yong Hu. Multiple method to probe extinction at cloud top.
- **Droplet Number Concentrations** (CNDC): Cloud Top Extinction combined from Polarimater Size Distributions used to retrieve Lidar ratio determined from optically opaque clouds following methods developed by Yong Hu.
  - Depends on the cloud droplet size distributions.
- **Cloud Lidar Ratio**:
  - HSRL technique provides unique method to normalize the measurements above the cloud (i.e. account for the attenuation above the cloud top)
  - Observe variations in lidar ratio that is larger than those determined from the size parameters from polarimeter. There is interest into better understanding these differences and how much variability existing. For example, do drizzling clouds reduce the lidar ratio (532nm).
- ACTIVATE offers opportunity to explore combined measurements from polarimeter, lidar, and compare results to the in situ measurements.

Flight Track and Lidar Backscatter (532nm): 29 Feb. 2020 Winter



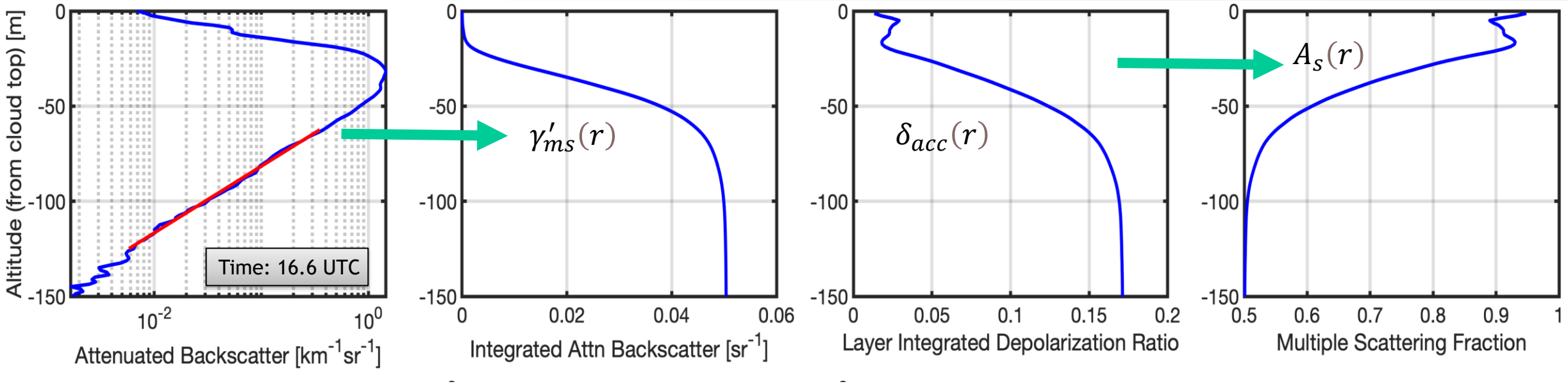






Zoomed View (cloud top)

Methodology of Cloud Extinction Profiles (Example 29 Feb. 2020)



Lidar transmission based on **integrated backscatter** and **multiple scattering ratio**; assumes constant lidar ratio.

$$T_p^2(r) = 1 - 2S_p A_s(r)\gamma'_{ms}(r)$$

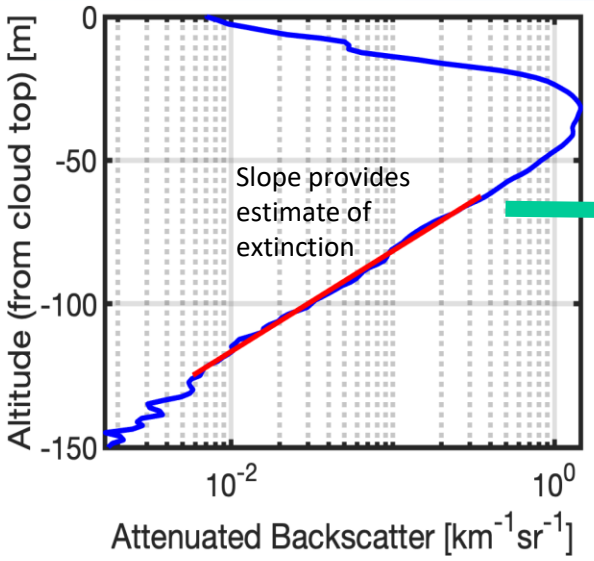
For opaque clouds (T≃0), we can determine the lidar ratio (S_p) from the integrated backscatter and depolarization.

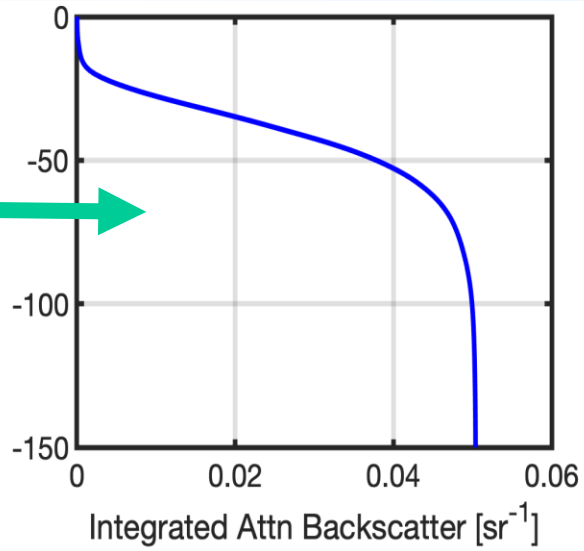
$$S_p = \frac{1}{2A_s\,\gamma'_{ms}}$$

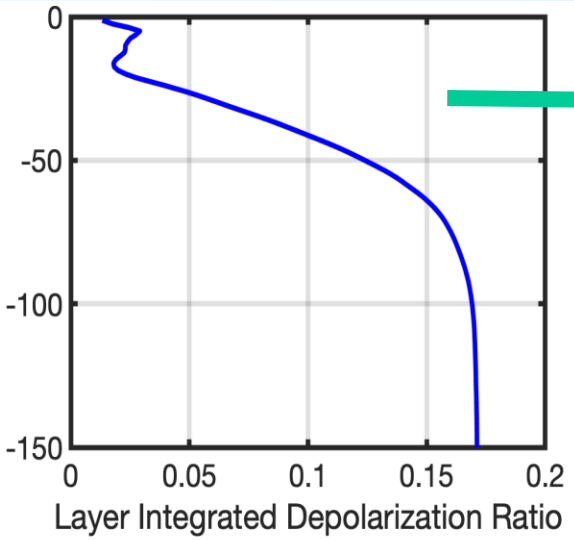
$$A_s(r) \equiv \frac{\gamma'_{ss}(r)}{\gamma'_{ms}(r)} \equiv \left(\frac{1-\delta_{acc}(r)}{1+\delta_{acc}(r)}\right)^2$$

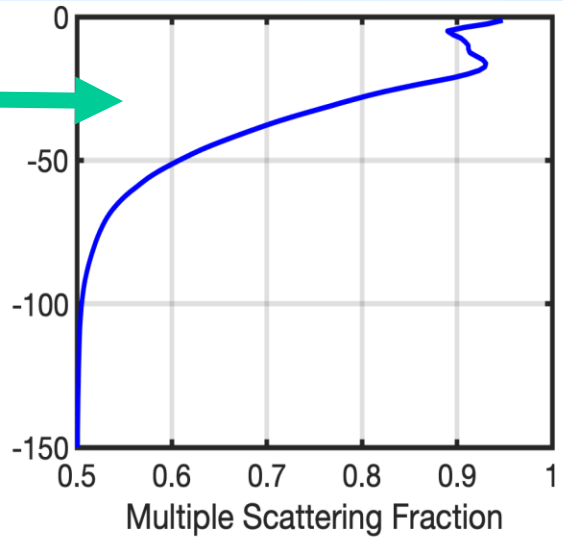
- A_s = single scattering/total scattering
- For liquid clouds, the multiple scattering can be determined from the lidar depolarization (Hu et. al, 2007)
- Not valid for ice or mixed phase clouds that have single scattering depolarization.

Example of Cloud Extinction Retrieval: 29 February 2020

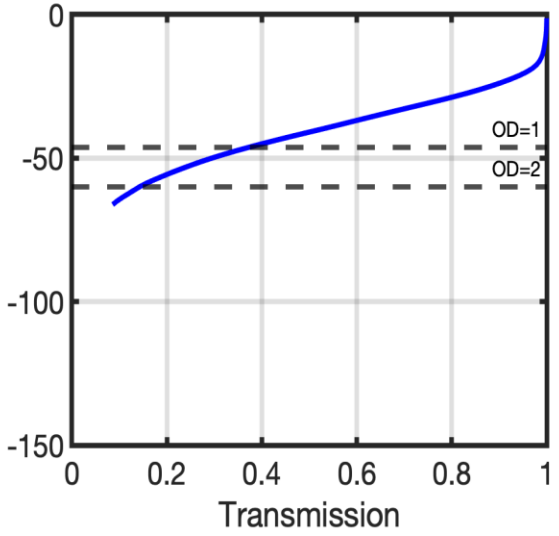


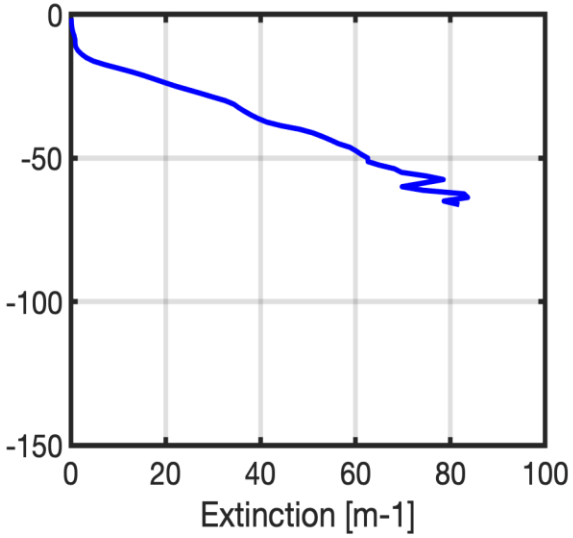






Cloud Top Height: 2078 m
Extinction (slope) = 66 km^{-1}
Extinction (average) = 49 km^{-1}
Extinction (@OD=1) = 59 km^{-1}
Extinction (@OD=2) = 70 km^{-1}
Cloud Depth (@ OD=1) = 49 m
Lidar Ratio = 19.8 sr





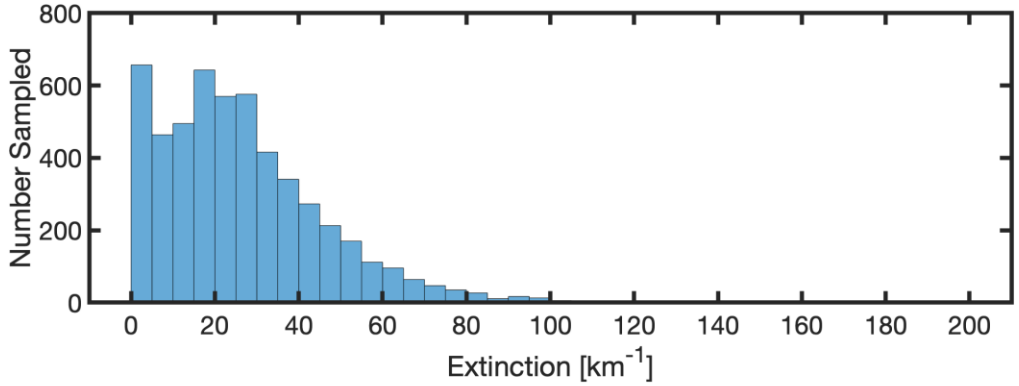
Note: Slope method is taken deeper (OD > 1)

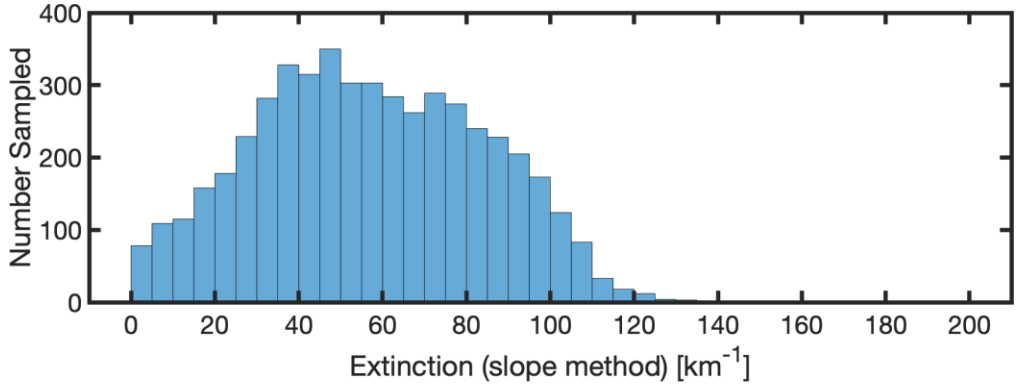
Cloud Top Extinction: compare two methods and with cloud probes, 29 February 2020

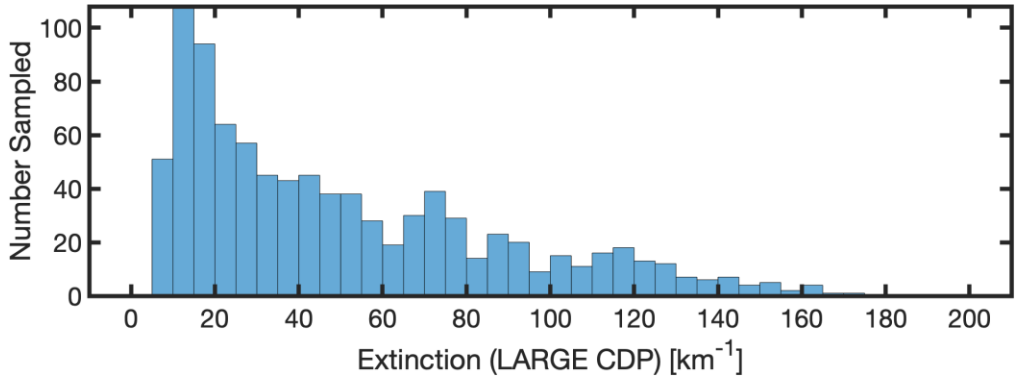
Averaged extinction (OD = 0.1-1) compares better to in situ measurements than the slope method for this flight.

Extinction determined from slope method is higher due to clouds being geometrically thin on this flight. Note, the method assumes a constant backscatter.

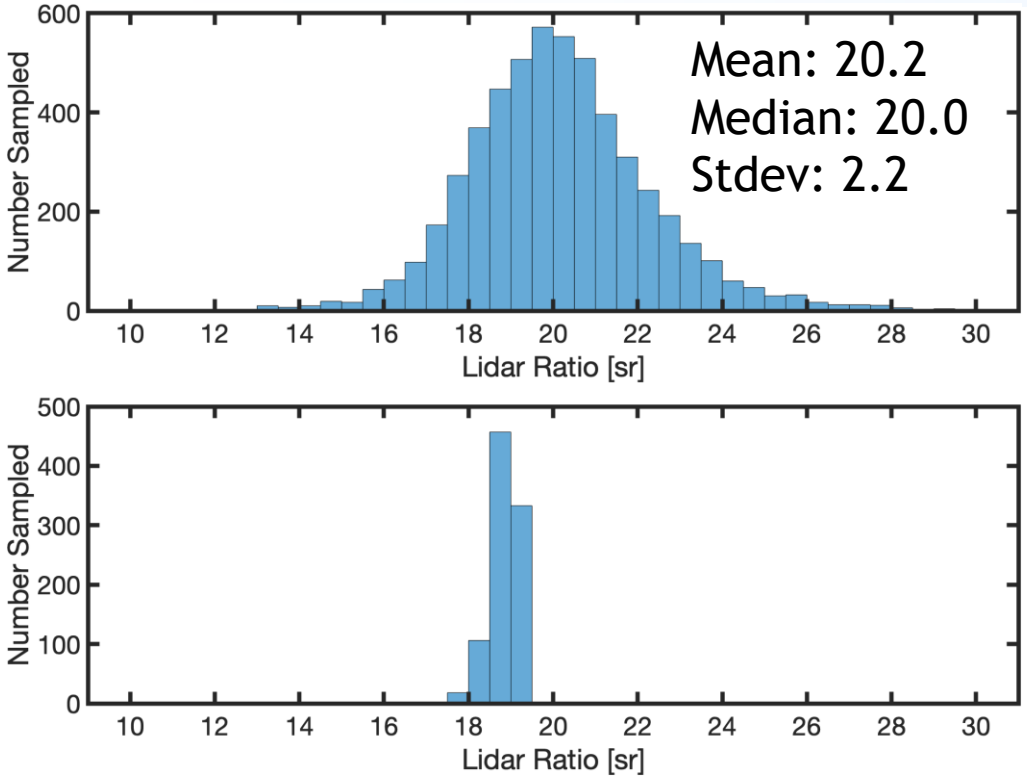
LARGE CDP (similar for FCDP) extinction is calculated based on the size distributions and number concentrations. Only BCT and ACT legs and LWC > 0.02 g/m^3 included.





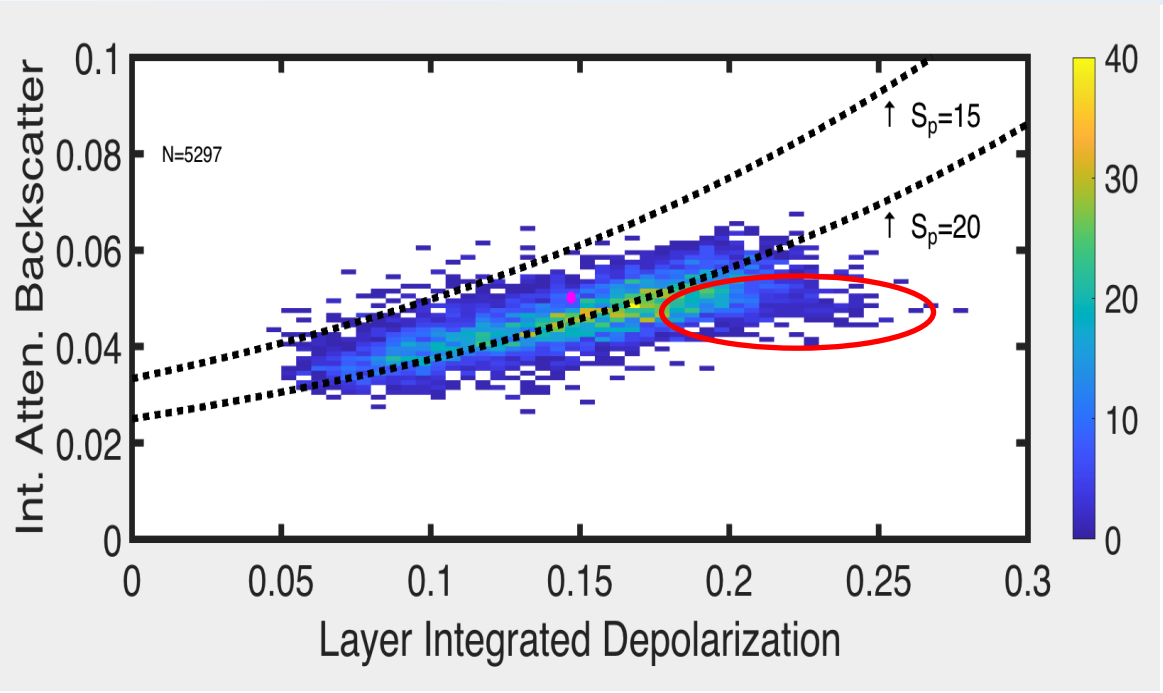


Derived lidar ratios are more variable and larger than in situ measurements



Small range for lidar ratios determined from measured in situ size distributions from ACT and BCT legs. Previous comparisons with RSP shows similar differences.

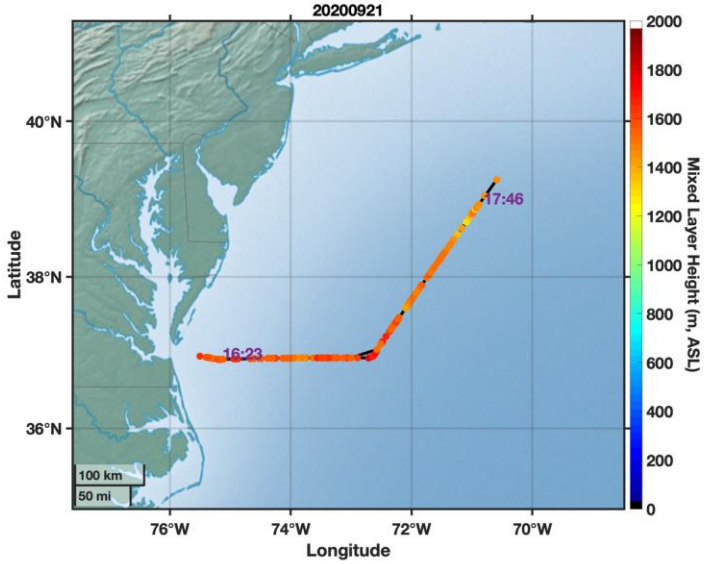
Mean lidar ratio is consistent with small effective radius (~5 microns)

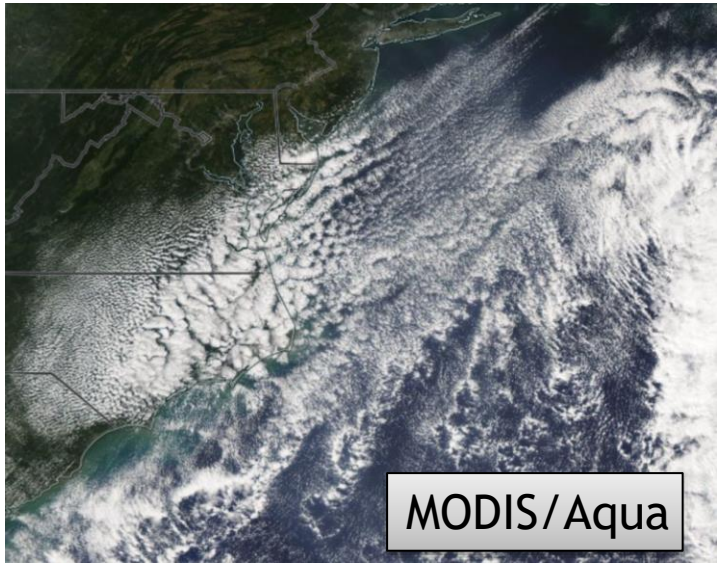


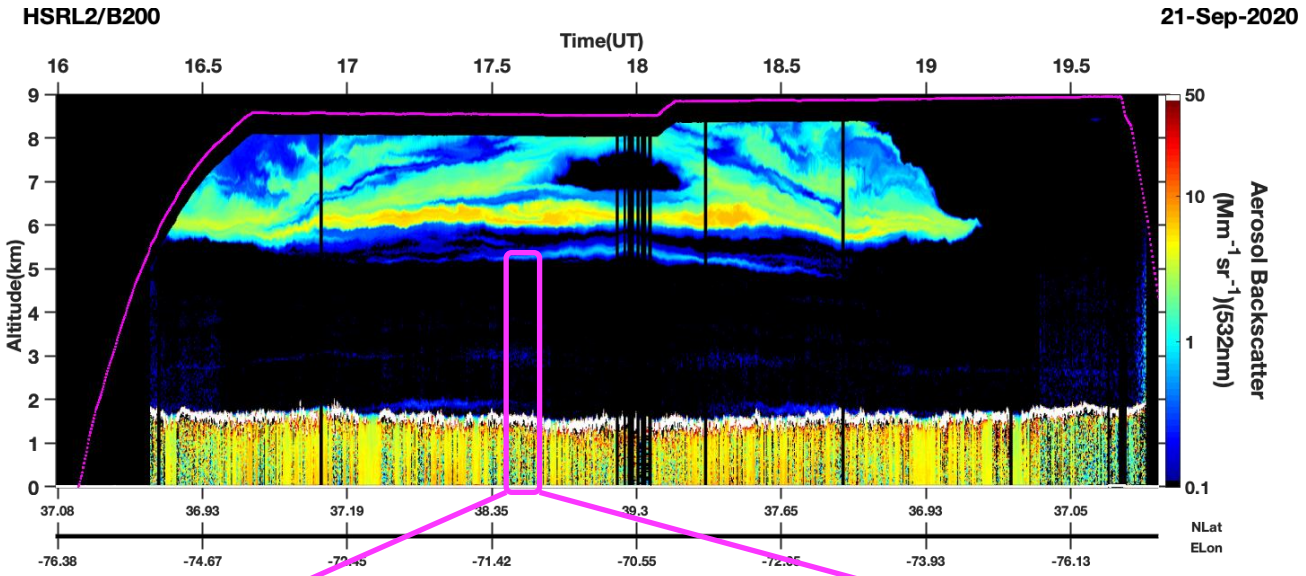
Lidar ratios are determined from integrated backscatter and depolarization. The above histogram shows the contours for the upper and lower limits expected from spherical particles.

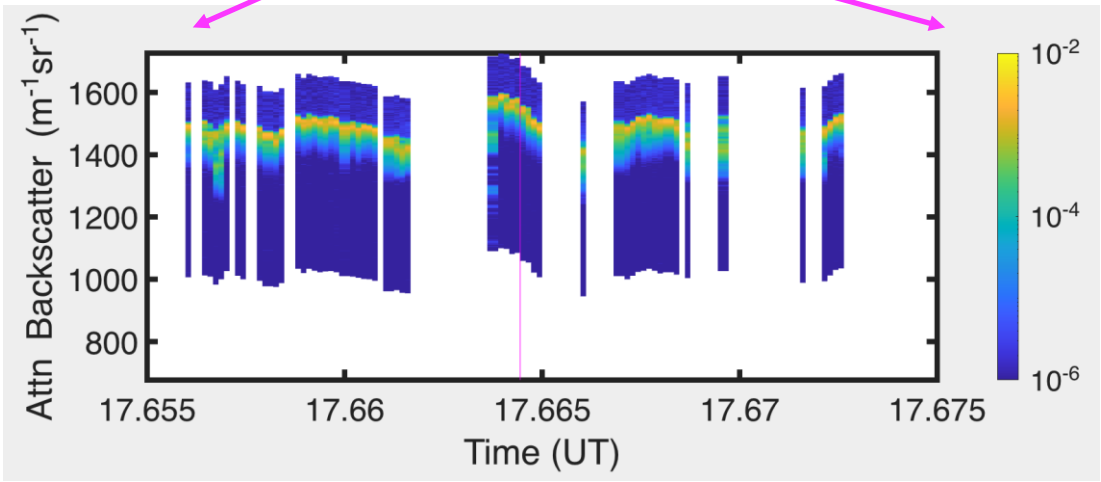
Note that larger values (circled) show higher depolarization values from ice or mixed phase clouds.

Summer Case: 21 September 2020

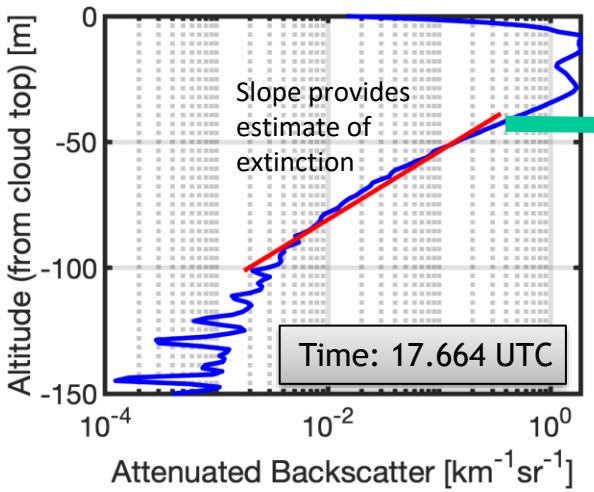


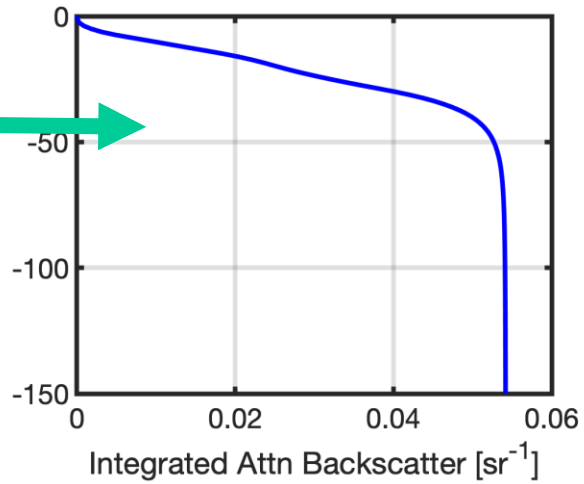


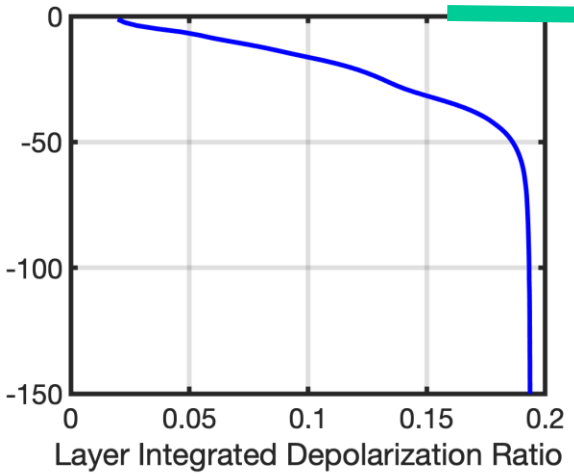


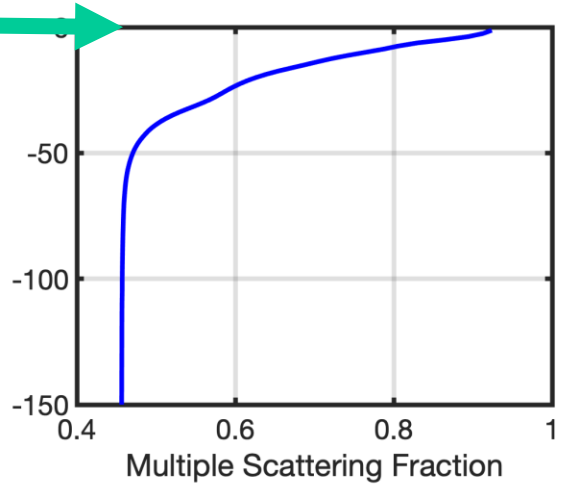


Example of Cloud Extinction Retrieval: 21 September 2020

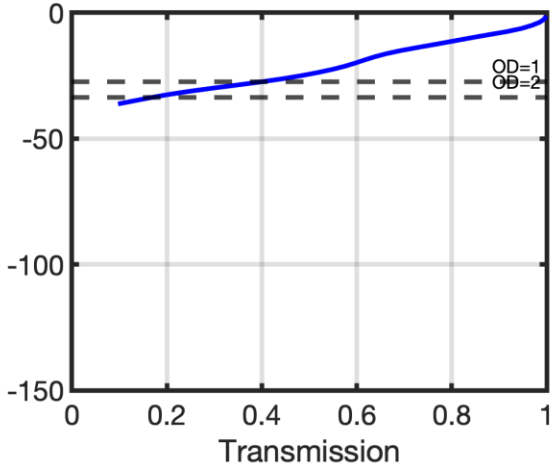


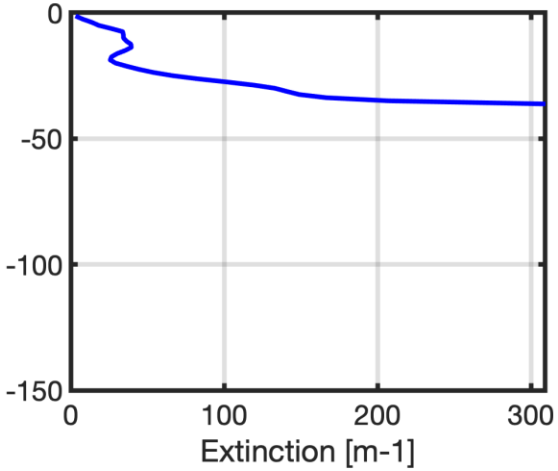






Cloud Top Height: 2078 m
Extinction (slope) = 93 km^{-1}
Extinction (average) = 53 km^{-1}
Extinction (@OD=1) = 102 km^{-1}
Extinction (@OD=2) = 166 km^{-1}
Cloud Depth (@ OD=1) = 27.5 m
Lidar Ratio = 20.3 sr





Forward Camera

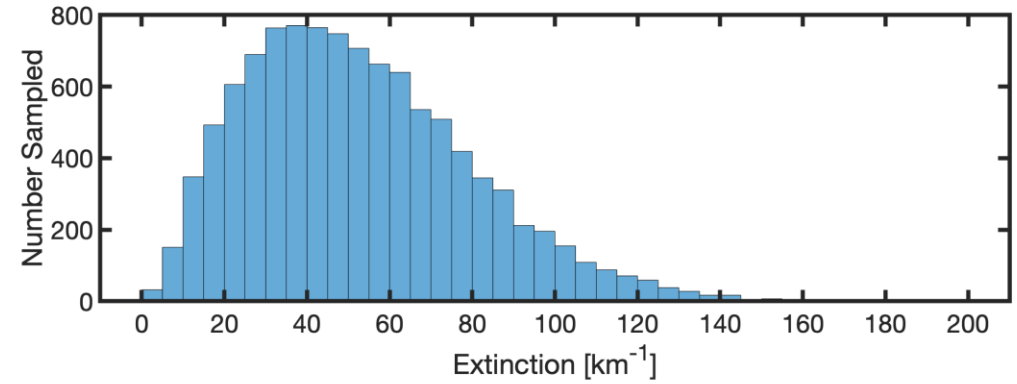
Note: Slope method is taken deeper (OD > 1)

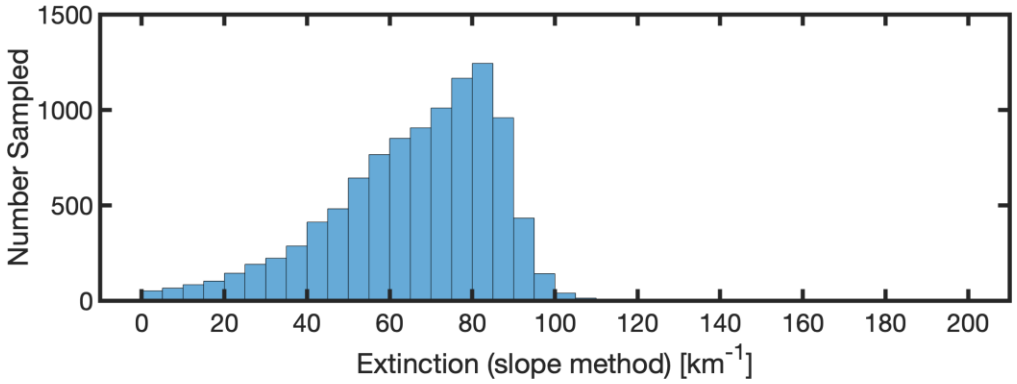
Cloud Top Extinction: compare two methods and with cloud probes, 21 September 2020

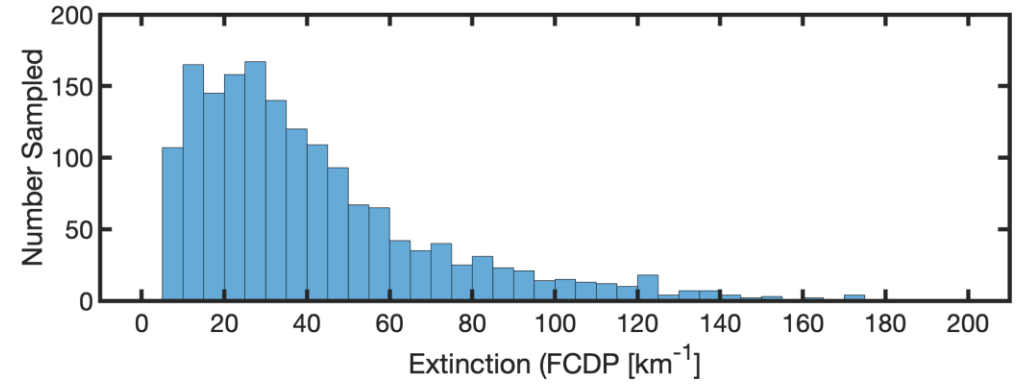
Averaged extinction (OD = 0.1-1) compares better to in situ measurements than the slope method for this flight.

Extinction determined from slope method is higher due to clouds being geometrically thin. Note, the method assumes a constant backscatter.

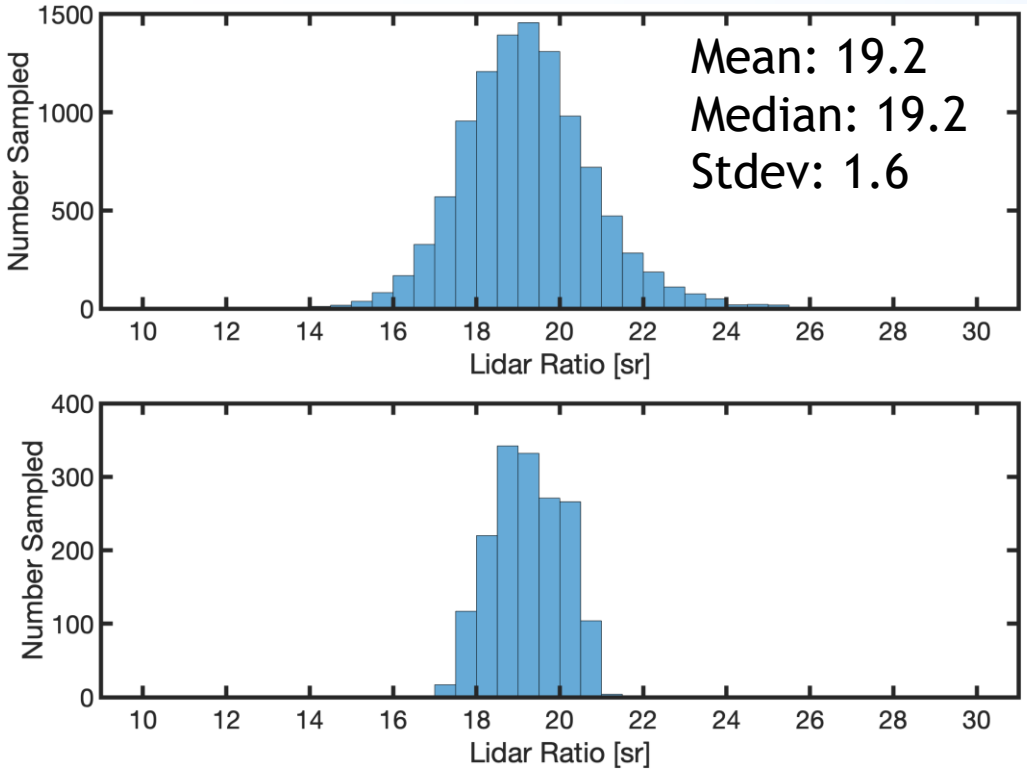
FCDP extinction is calculated based on the size distributions and number concentrations. Only BCT and ACT legs and LWC > 0.02 g/m^3 included. Lidar data is higher than in situ data.





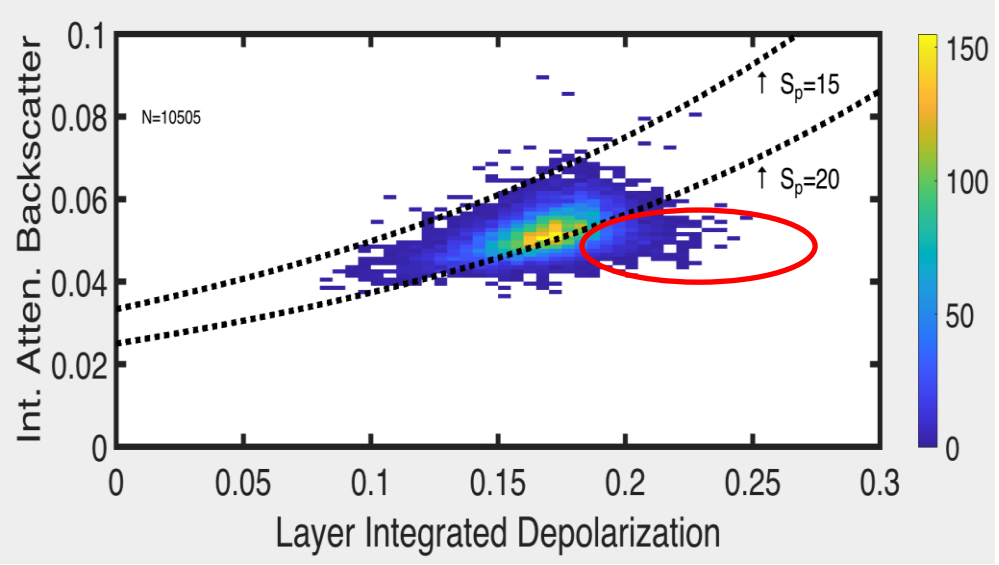


Derived lidar ratios are more variable and larger than in situ measurements, 21 September 2020



Small range for lidar ratios determined from measured in situ size distributions from ACT and BCT legs and match lidar.

Mean lidar ratio is consistent with small effective radius (~5 microns).



Lidar ratios are determined from integrated backscatter and depolarization. The above histogram shows the contours for the upper and lower limits expected from spherical particles.

Note that larger values (circled) show higher depolarization values from ice or mixed phase clouds still present but less than winter.