

Airborne High Spectral Resolution Lidar Measurements of Aerosol Distributions and Properties during the NASA DISCOVER-AQ and SEAC4RS Missions

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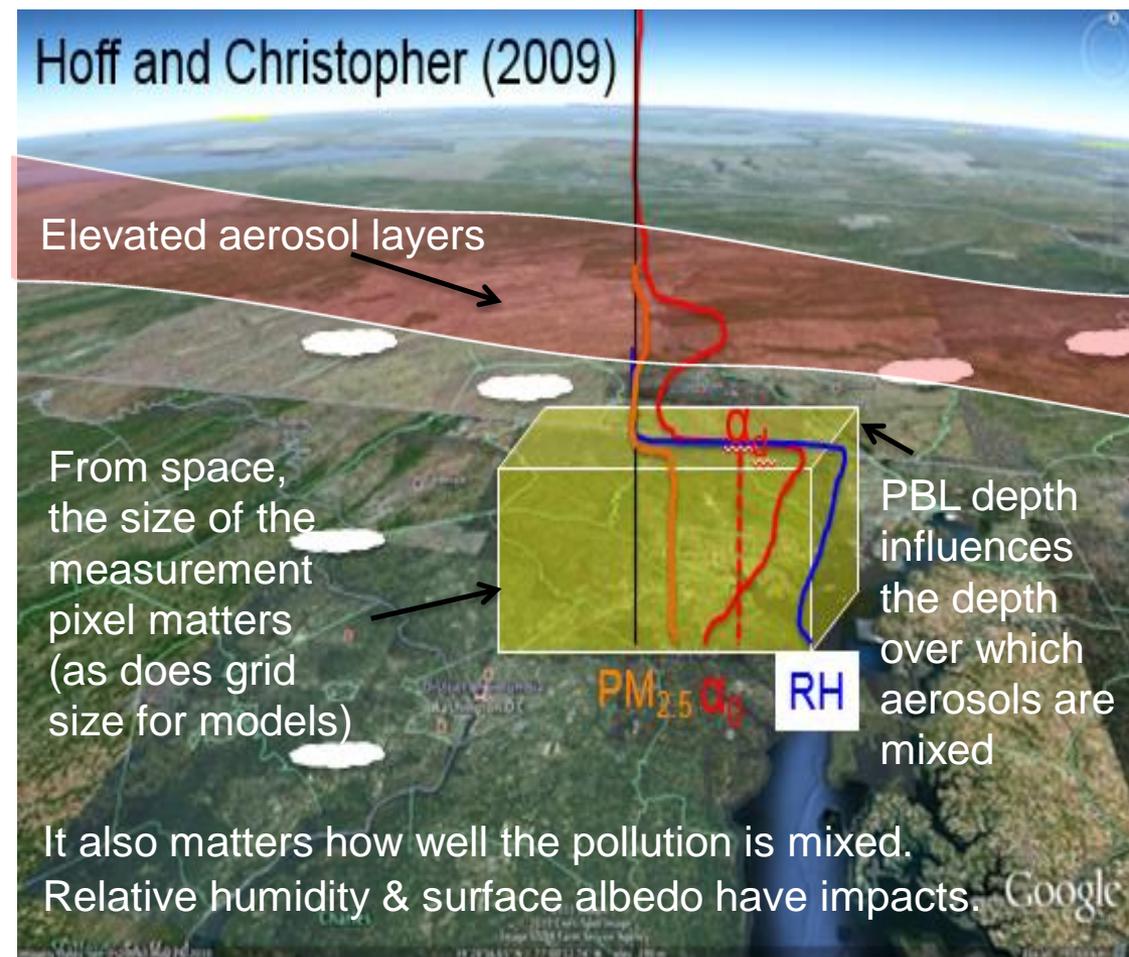
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Problem – Several factors complicate satellite retrievals of surface air quality



Satellite retrievals of near-surface air quality information (e.g. $PM_{2.5}$) typically use column-integrated quantities (i.e. Aerosol Optical Thickness – AOT) obtained by passive remote sensors



What do we use for the height of the aerosols? Mixed Layer (ML) height?

Can we assume that near-surface aerosol extinction is about the same as the mean aerosol extinction in the ML?

How well is near-surface extinction related to surface $PM_{2.5}$?

How well can column AOT be used to infer near-surface aerosol extinction and $PM_{2.5}$?

Deriving Information on Surface Conditions from Column and VERTically Resolved Observations Relevant to Air Quality

A NASA Earth Venture campaign intended to improve the interpretation of current and future satellite observations to diagnose near-surface conditions relating to air quality

Objectives:

1. **Relate column observations to surface conditions** for aerosols and key trace gases O_3 , NO_2 , and CH_2O
2. **Characterize differences in diurnal variation** of surface and column observations for key trace gases and aerosols
3. **Examine horizontal scales of variability** affecting satellites and model calculations

Deployments and key collaborators

Maryland, July 2011 (EPA, MDE, UMD, UMBC, Howard U.)

California, January 2013 (EPA, CARB, UC-Davis&Irvine)

Texas, September 2013 (EPA, TCEQ, U. of Houston)

Colorado, Summer 2014 (EPA, NSF, NOAA, CDPHE)





- NASA/LaRC King Air
- Flight altitude ~ 9 km
- Nadir pointing lidar

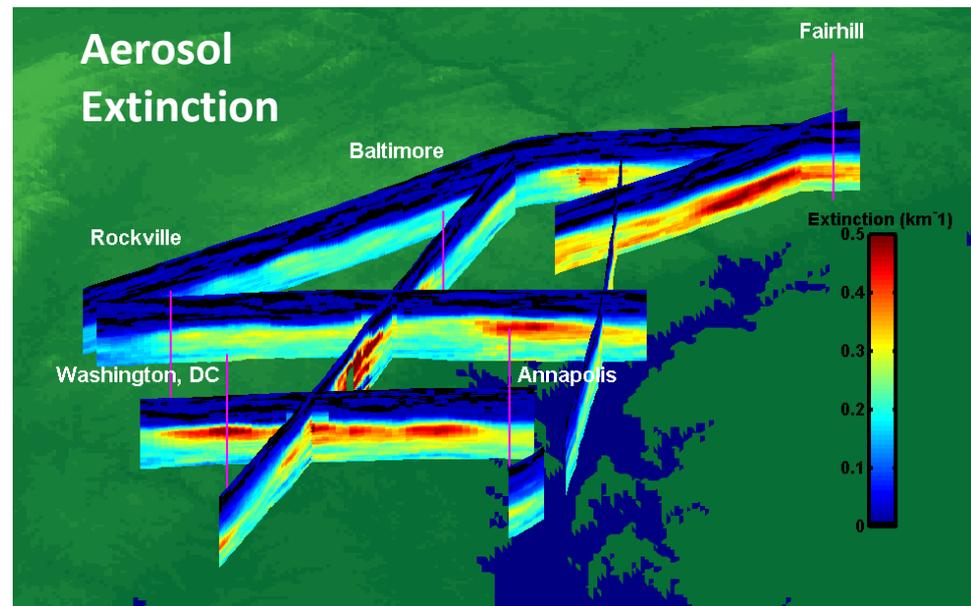
HSRL Technique:

- Independently measures aerosol backscatter, extinction, and optical thickness

HSRL(-2) Aerosol Data Products:

- Backscatter coefficient (355, 532, 1064 nm)
- Depolarization (355, 532, 1064 nm)
- Extinction Coefficient (355, 532 nm)
- Optical Depth (AOD) (355, 532 nm)
- Aerosol Typing
- Mixed Layer (ML) Heights

- HSRL-1 deployed for DAQ-1 (DC-Baltimore)
- HSRL-2 developed as a prototype of multiwavelength lidar for NASA Aerosol-Clouds-Ecosystem (ACE) mission
- HSRL-2 capability at 355, 532 nm
- Provide “ $3\beta+2\alpha$ ” suite of measurements for aerosol microphysical retrievals
- HSRL-2 used for final three DISCOVER-AQ deployments (California, Houston, Denver)

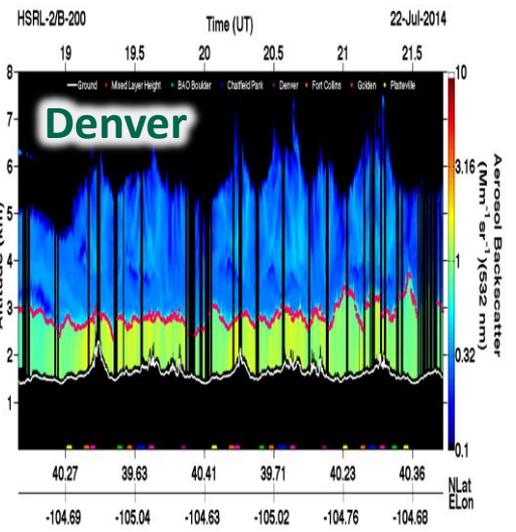
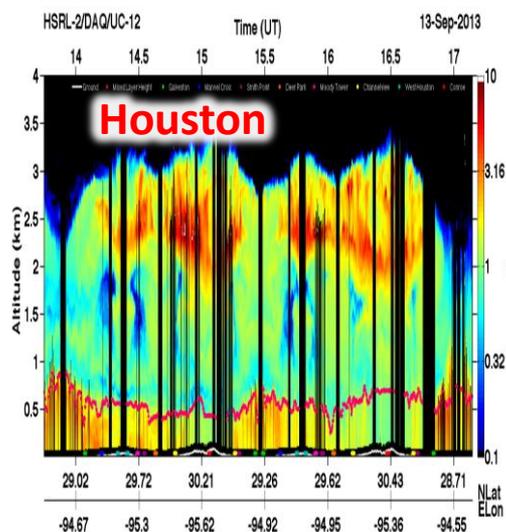
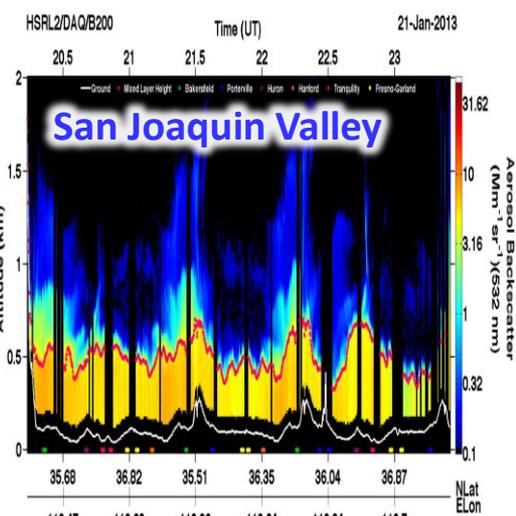
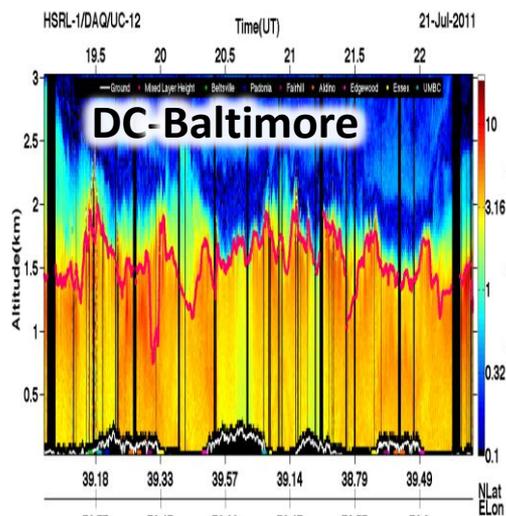


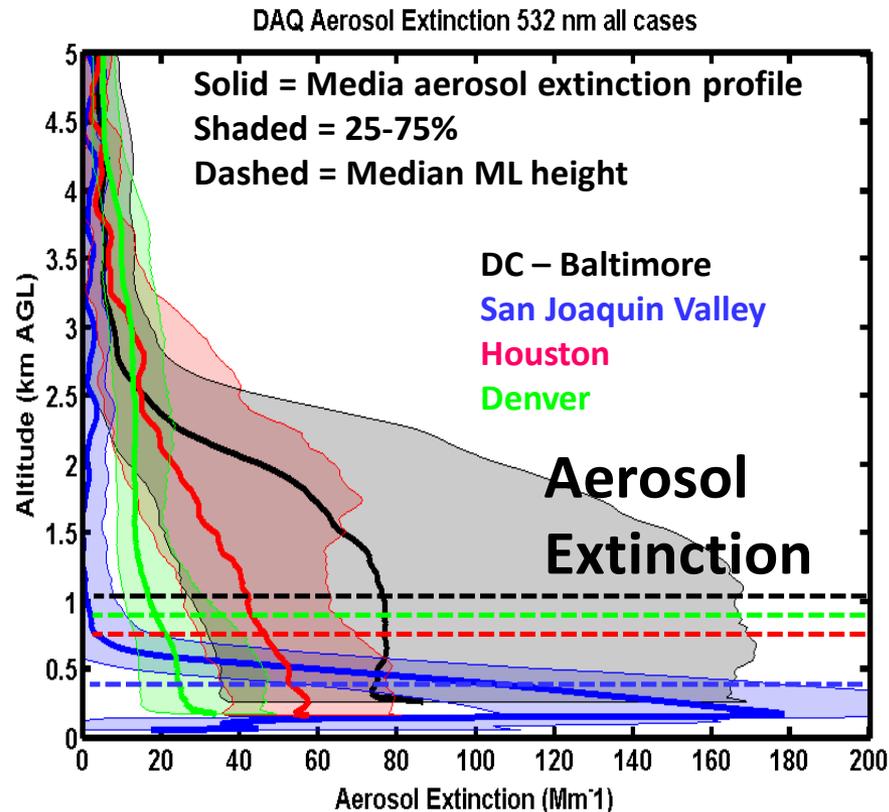
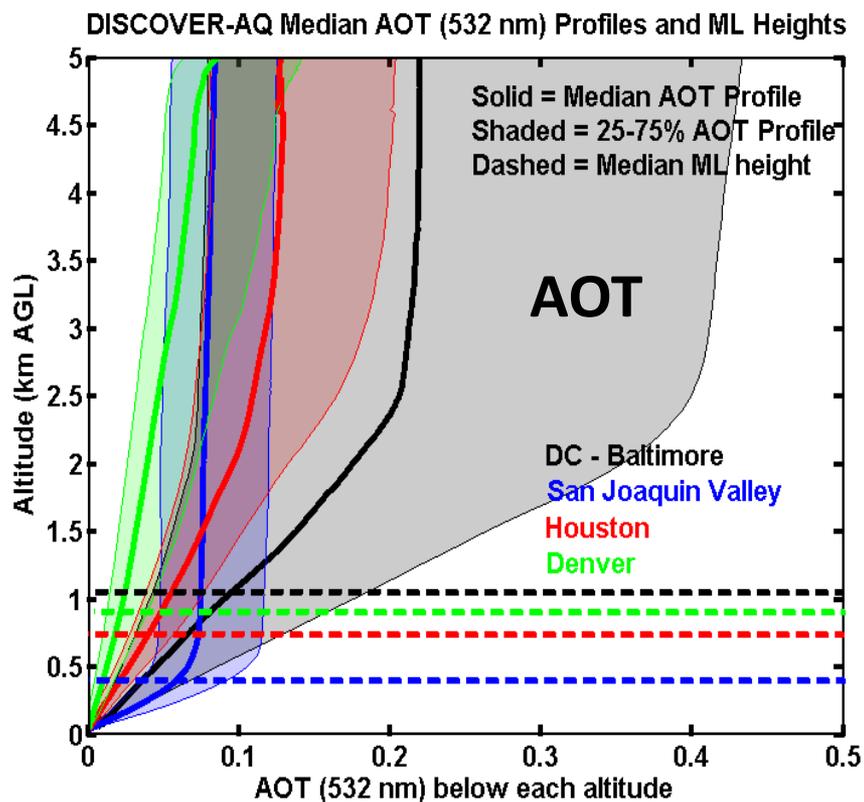
Mixed Layer Heights and Median Aerosol Profiles



HSRL Mixed Layer Heights

- Mixed Layer (ML) heights derived from daytime-only cloud-screened aerosol backscatter profiles
- ML heights are good proxy for daytime PBL heights
- Technique uses a Haar wavelet covariance transform with multiple wavelet dilations to identify sharp gradients in aerosol backscatter (adapted from Brooks, JAOT, 2003)
- Automated HSRL algorithm chooses ML from among aerosol gradients with input from manual inspection where necessary

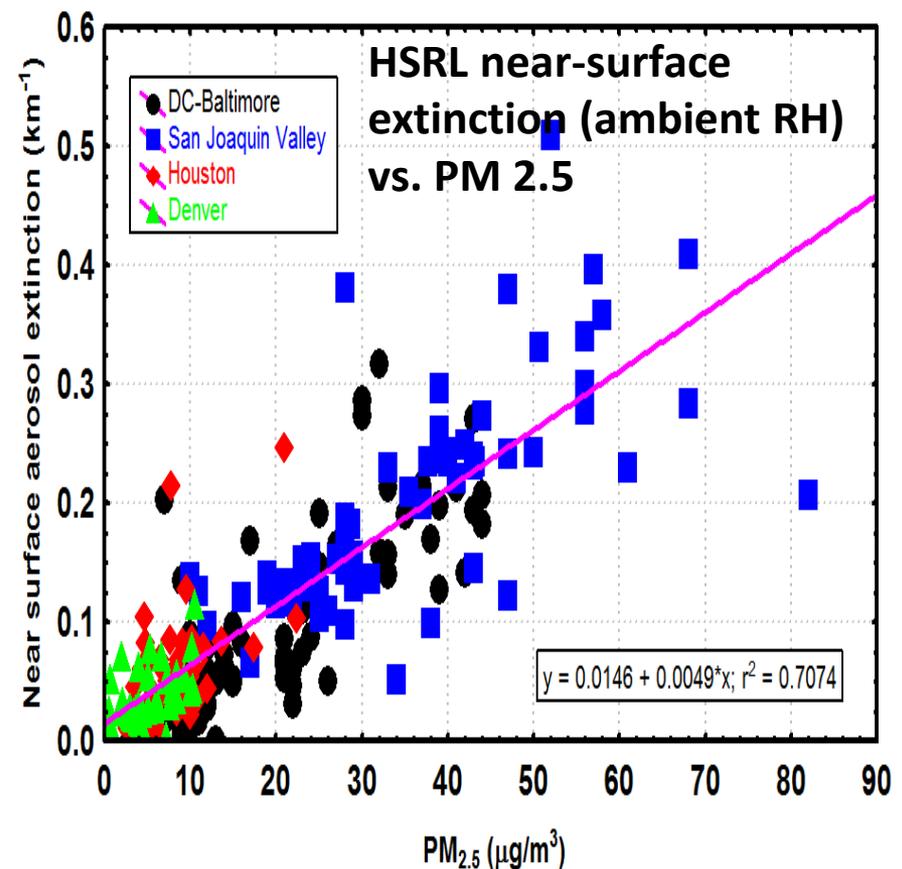
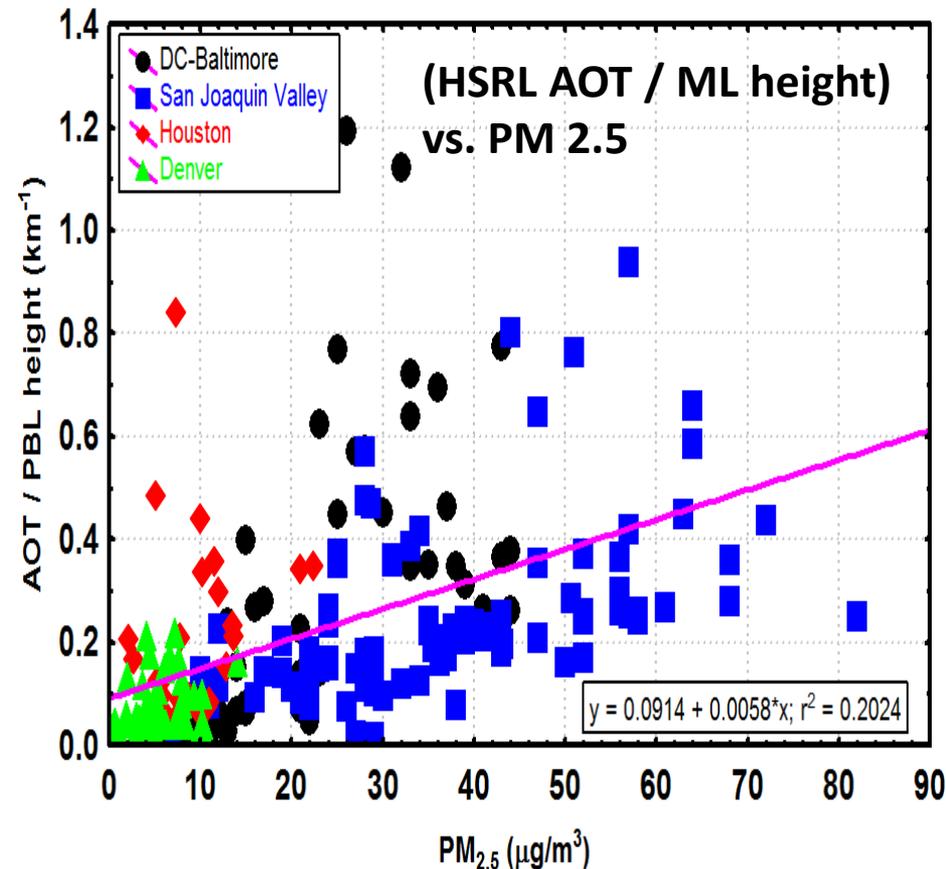




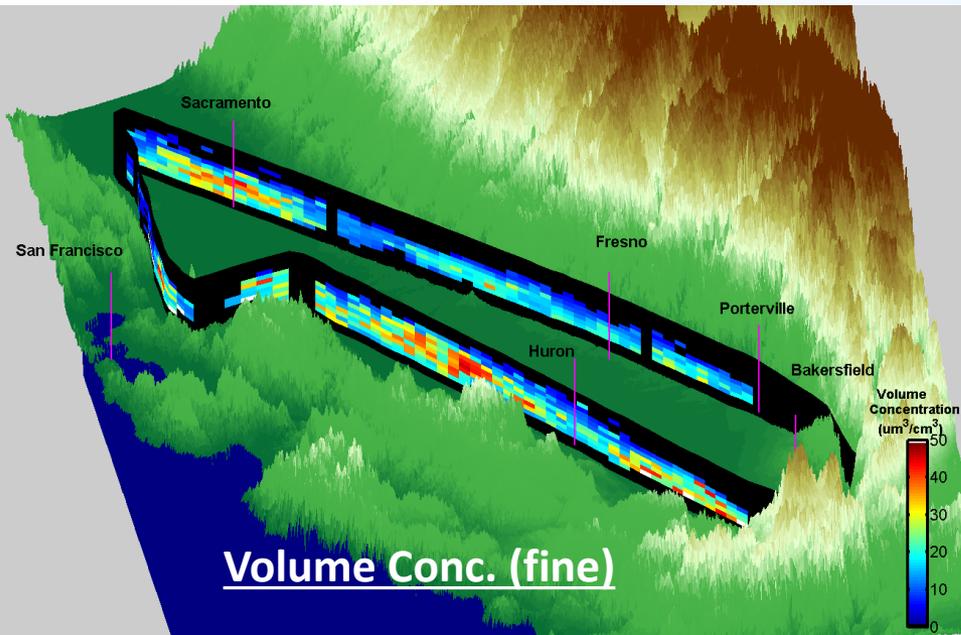
- AOT profiles and ML heights computed for four DISCOVER-AQ missions
- DC-Baltimore had largest median column AOT values
- Median AOT values in the later three campaign were comparable
- With exception of San Joaquin Valley, median profiles show that about only about 20-65% of AOT was within mixed layer; much of AOT was above mixed layer
- In San Joaquin Valley, most (>80%) of AOT was within mixed layer

HSRL Measurements and Surface PM_{2.5}

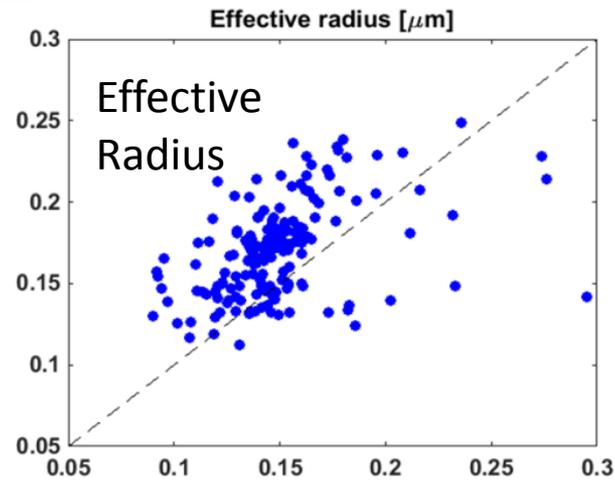
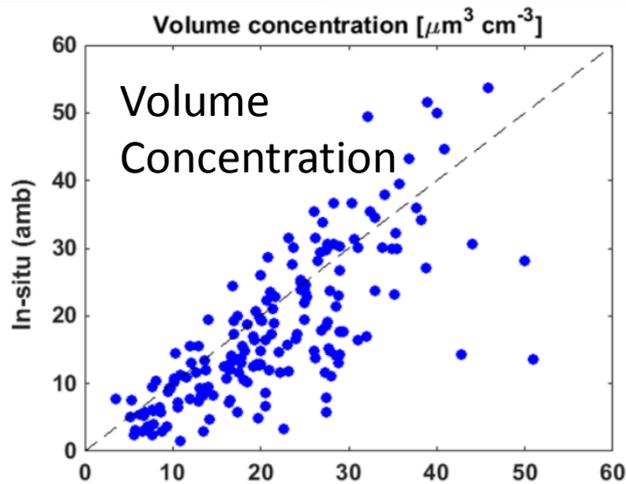
- In certain locations and cases, surface $PM_{2.5}$ can be inferred from measurements of AOT and height of the aerosol layer
- However, HSRL data show $PM_{2.5}$ is much better correlated with near surface extinction than AOT scaled by aerosol layer or ML heights



HSRL-2 Multiwavelength Aerosol Retrievals and Surface $PM_{2.5}$



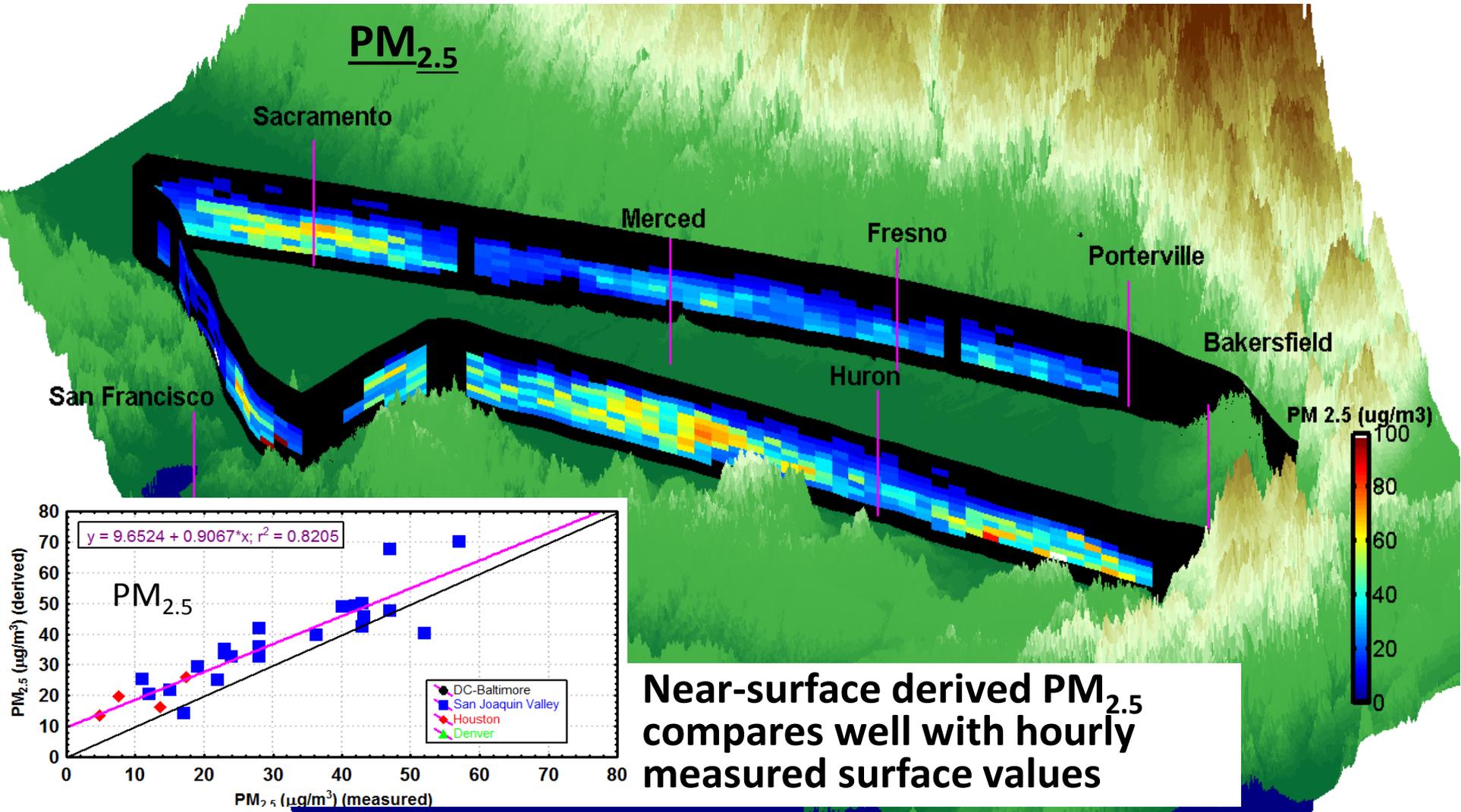
- HSRL-2 multiwavelength measurements of aerosol backscatter and extinction were used to retrieve fine mode aerosol volume concentration and effective radius (e.g. Müller et al., 2014)
- Sawamura et al. (ACPD, 2016) shows the retrievals compare reasonably well with P-3 airborne in situ data



HSRL-2 (fine mode)

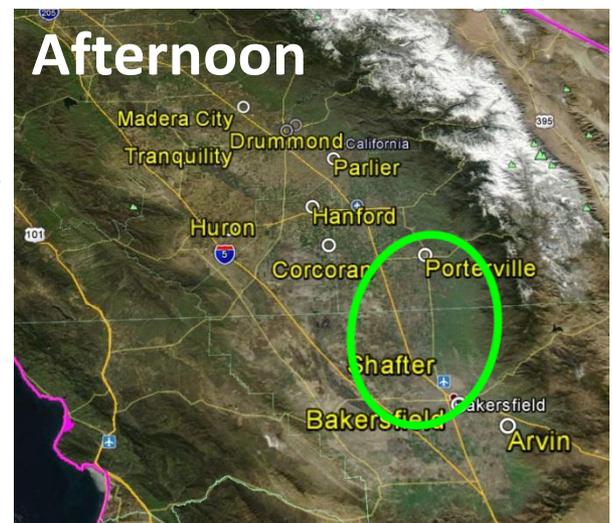
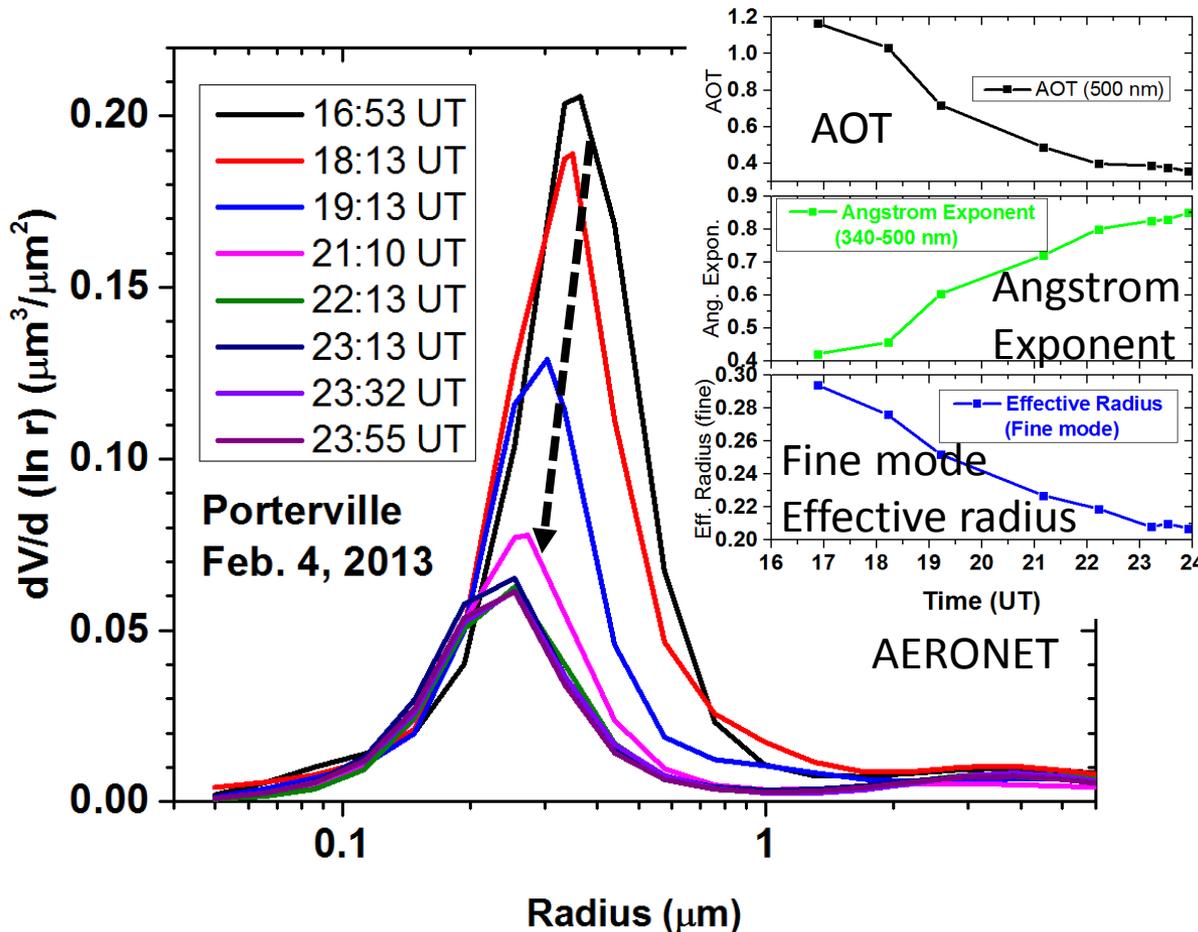
(Number of points = 173)

HSRL-2 multiwavelength retrievals of fine mode volume concentration were used with assumed particle density to derive PM_{2.5}



HSRL-2 Multiwavelength Aerosol Retrievals Used to Investigate Impacts of Large RH Variability on Aerosol Optical and Microphysical Properties

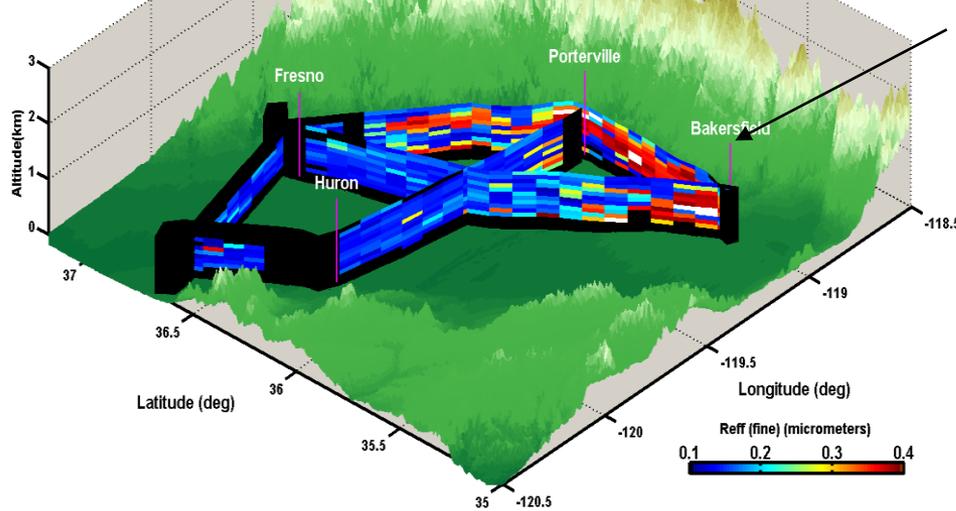
- Large decrease in AOT and fine mode size over the southern portion of DRAGON AERONET on Feb. 4
- This decrease occurred as fog processed and/or humidified aerosols transitioned to dried aerosol



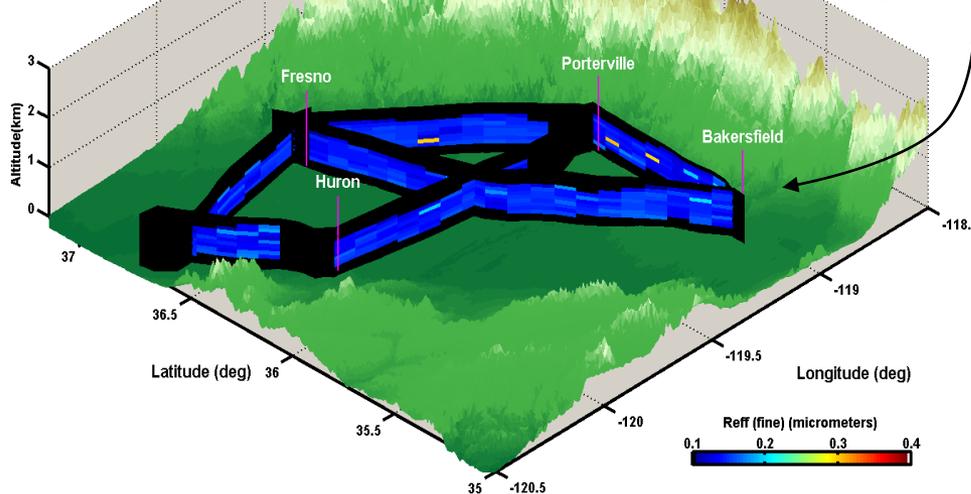
NASA/LaRC HSRL-2 multiwavelength aerosol retrievals show temporal, horizontal, and vertical variability in fine mode effective radius



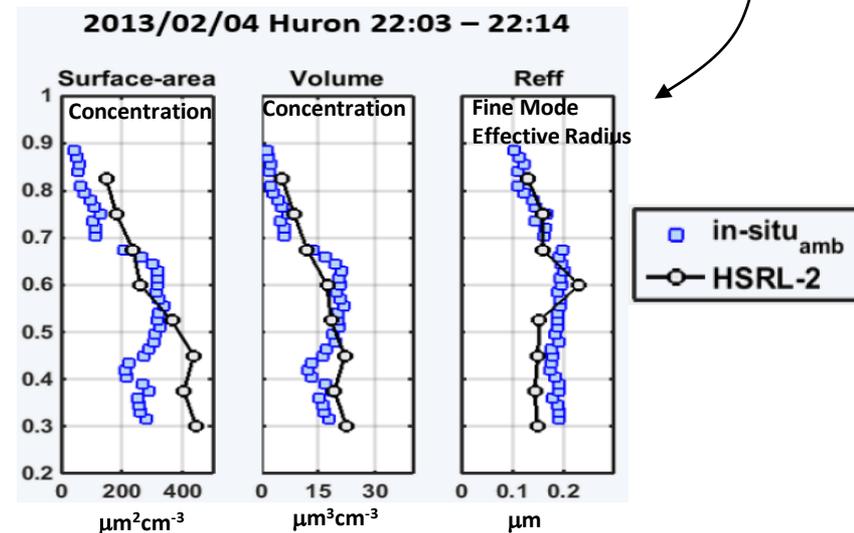
Fine Mode Effective Radius (morning flight)



Fine Mode Effective Radius (afternoon flight)



- Large decrease in fine mode effective radius between morning and afternoon as clouds and fog dissipated over the southeastern California Central Valley on February 4, 2013
- HSRL-2 multiwavelength retrievals of concentration and effective radius in good agreement with coincident airborne *in situ* measurements (Sawamura et al., ACPD, 2016)



DIAL/HSRL Comparisons with GEOS-5 During SEAC4RS



Airborne DIAL/HSRL Aerosol Measurements



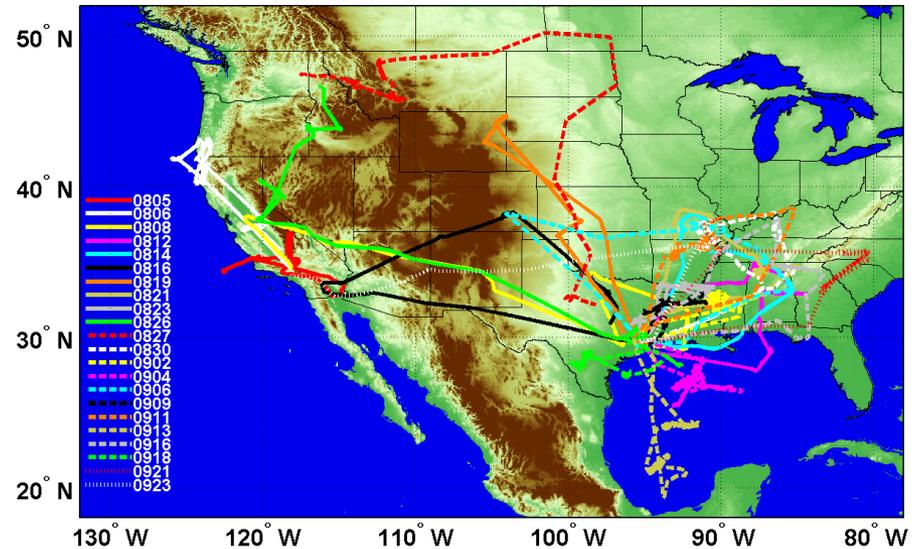
- NASA DC-8
- Flight altitude ~ 0.2-12 km
- Nadir and zenith pointing lidar

HSRL Technique:

- Independently measures aerosol backscatter, extinction, and optical thickness

DIAL/HSRL Aerosol Data Products:

- Backscatter coefficient (532,1064 nm)
- Depolarization (532,1064nm)
- Extinction Coefficient (532nm)
- Optical Depth (AOD) (532nm)
- Aerosol Typing
- Mixed Layer (ML) Heights



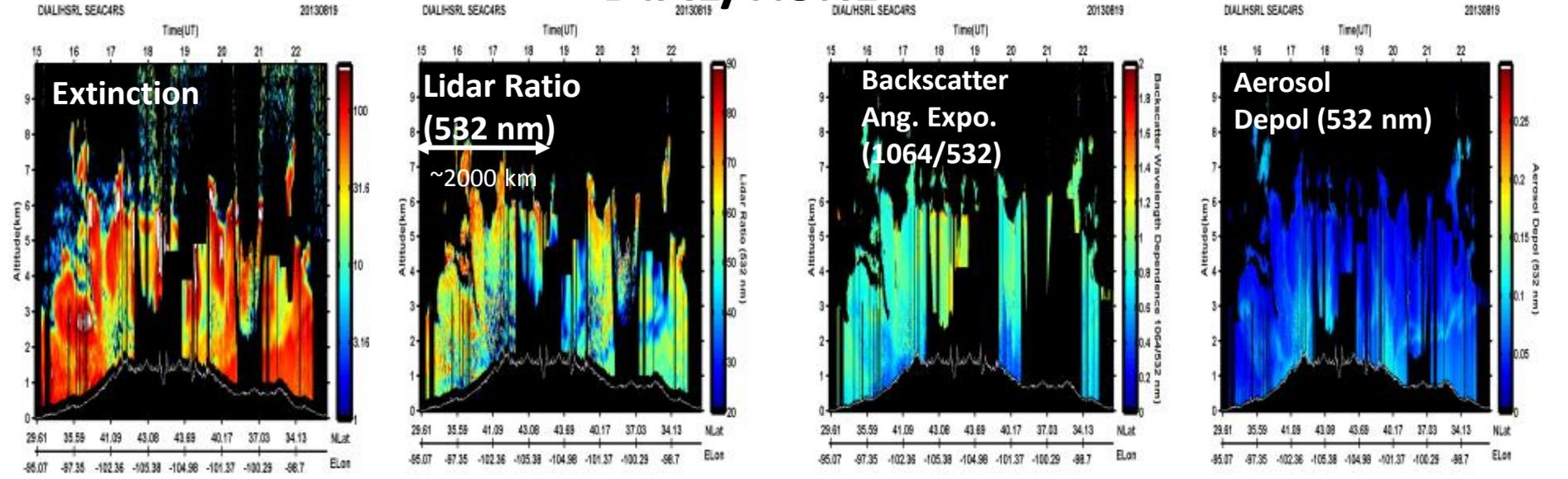
DIAL/HSRL

- Typically deployed from NASA DC-8 aircraft for long duration flights
- First ozone DIAL
- Long Heritage ~30 years of providing ozone and relative aerosol profiles.
- Measurements from NASA SEAC4RS mission in 2013 used here to evaluate NASA GEOS-5 and ECMWF/MACC-II models

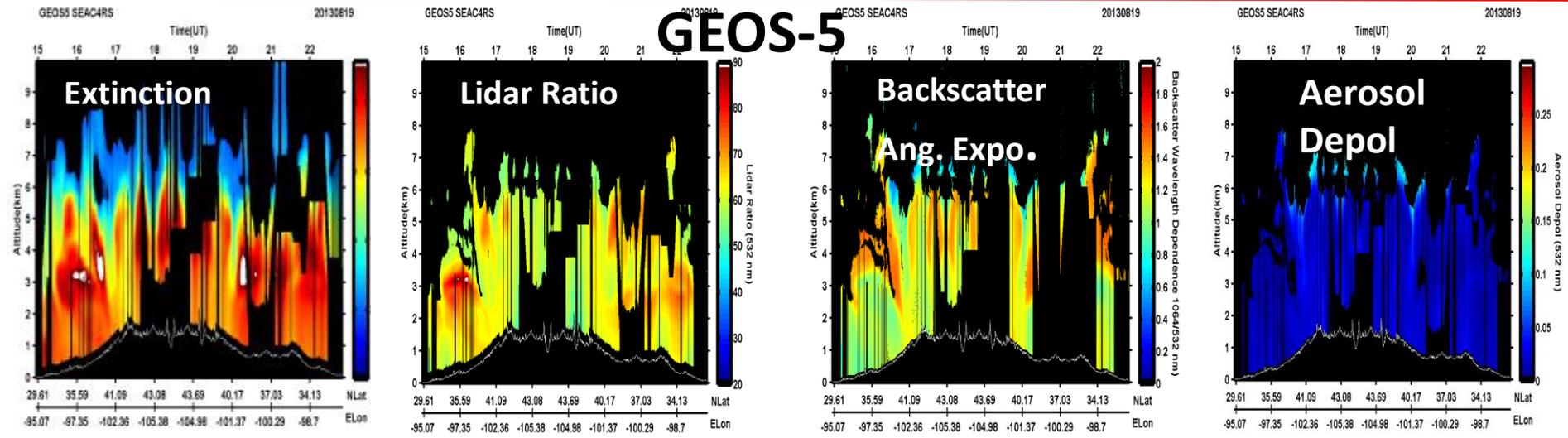
SEAC4RS Aug. 19, 2013 DIAL/HSRL Smoke flight over Midwest



DIAL/HSRL



GEOS-5

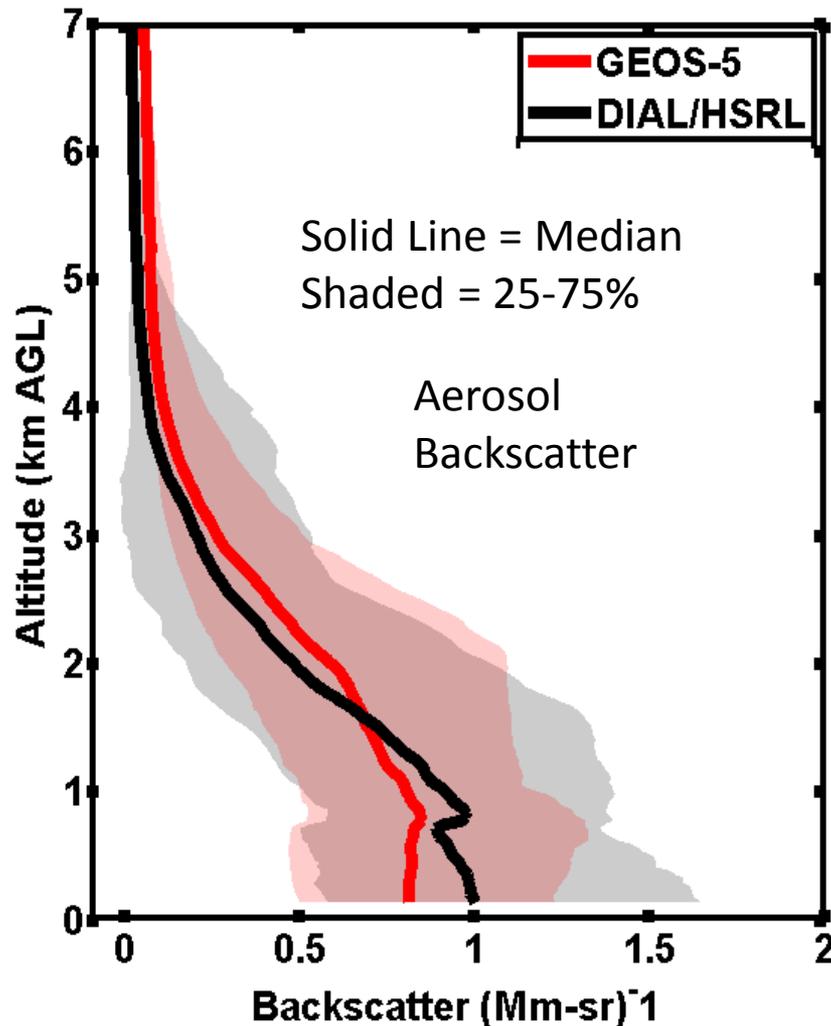


DIAL/HSRL and GEOS-5 Median Backscatter and Extinction Profiles During SEAC4RS

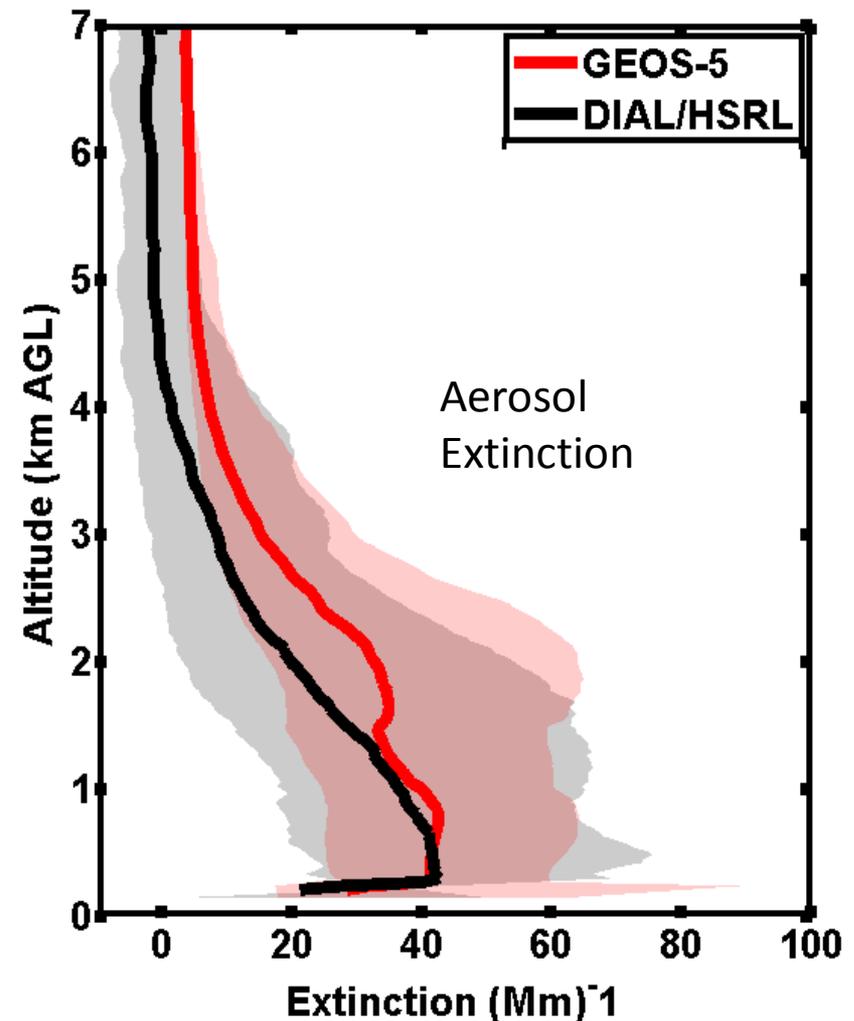


GEOS-5 shows slightly higher backscatter and extinction in free troposphere

SEAC4RS Aerosol Backscatter 532 nm all cases



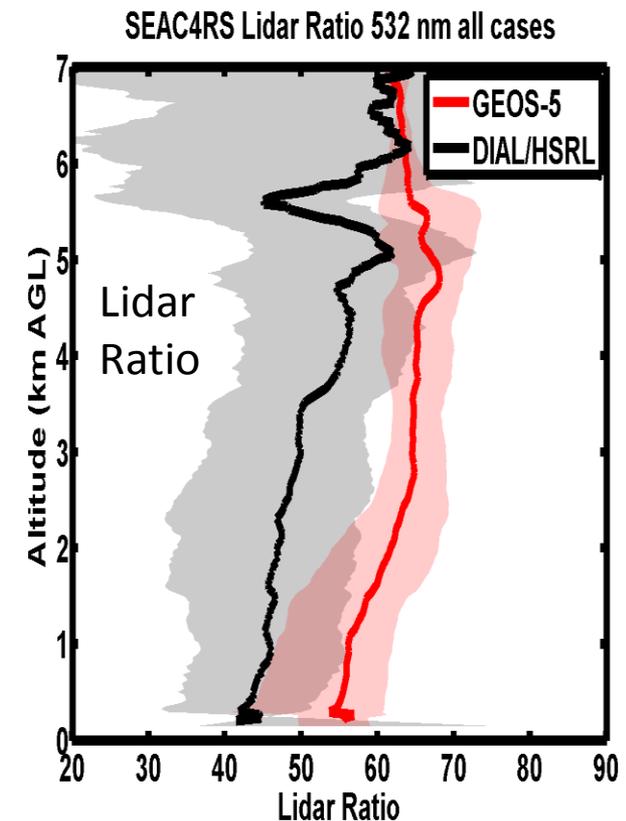
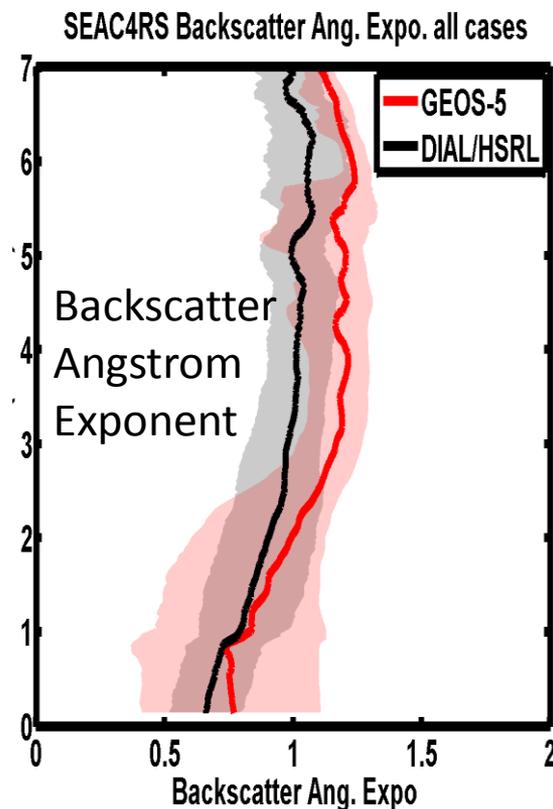
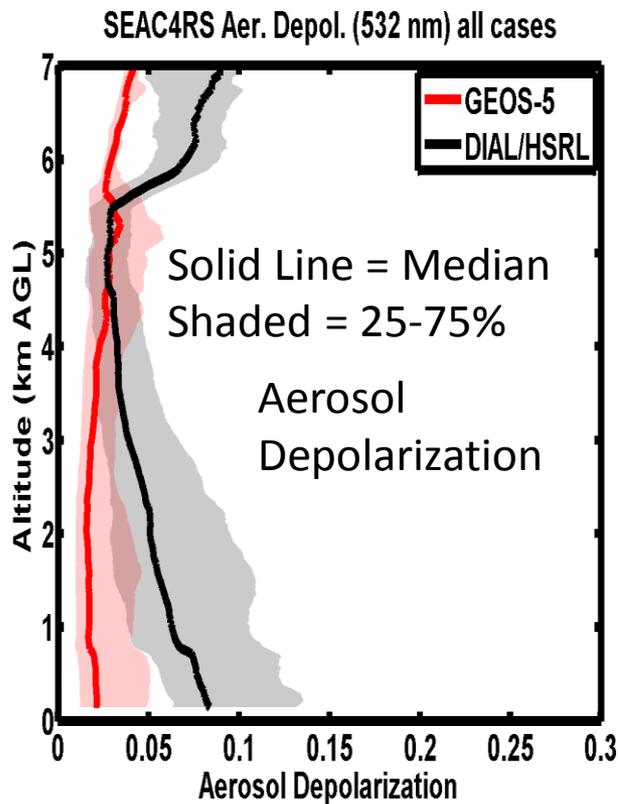
SEAC4RS Aerosol Extinction 532 nm all cases



DIAL/HSRL and GEOS-5 Median Intensive Parameter Profiles During SEAC4RS



- Both DIAL/HSRL and GEOS-5 intensive parameters vary with altitude suggesting aerosol type varies with altitude
- Backscatter Angstrom exponent increasing with altitude suggests decreasing particle size with height
- GOES-5 lidar ratio higher than DIAL/HSRL
- DIAL/HSRL measured more nonspherical particles (i.e. dust) near the surface than represented by GEOS-5

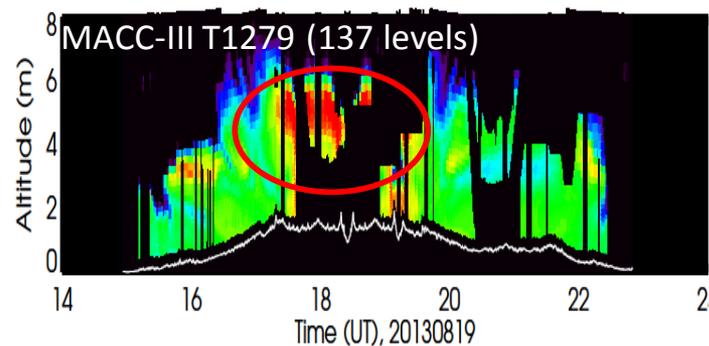
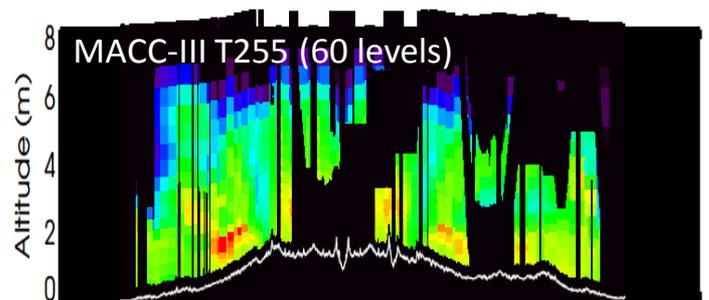
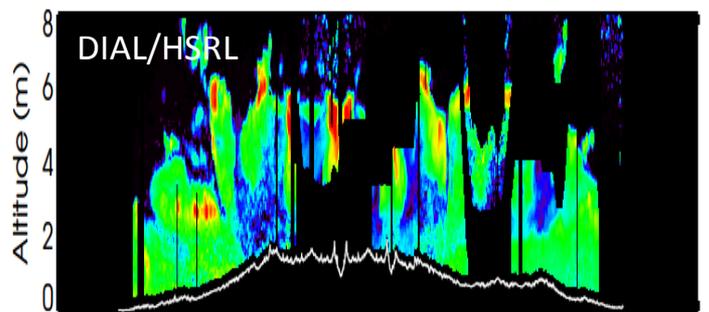


**DIAL/HSRL Comparisons with
ECMWF/MACC-III Model
During SEAC4RS**

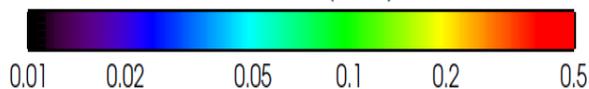
Evaluating the impact of higher model resolution



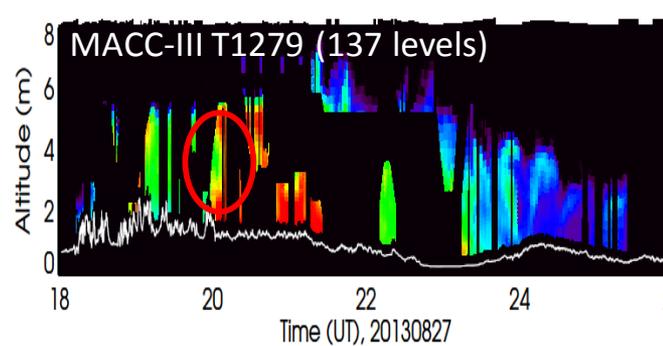
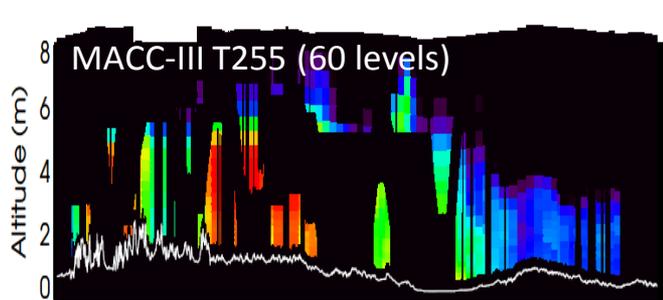
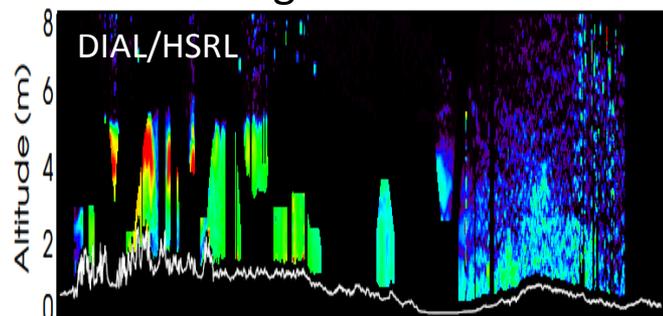
August 19



Extinction (km^{-1})



August 27



Extinction (km^{-1})



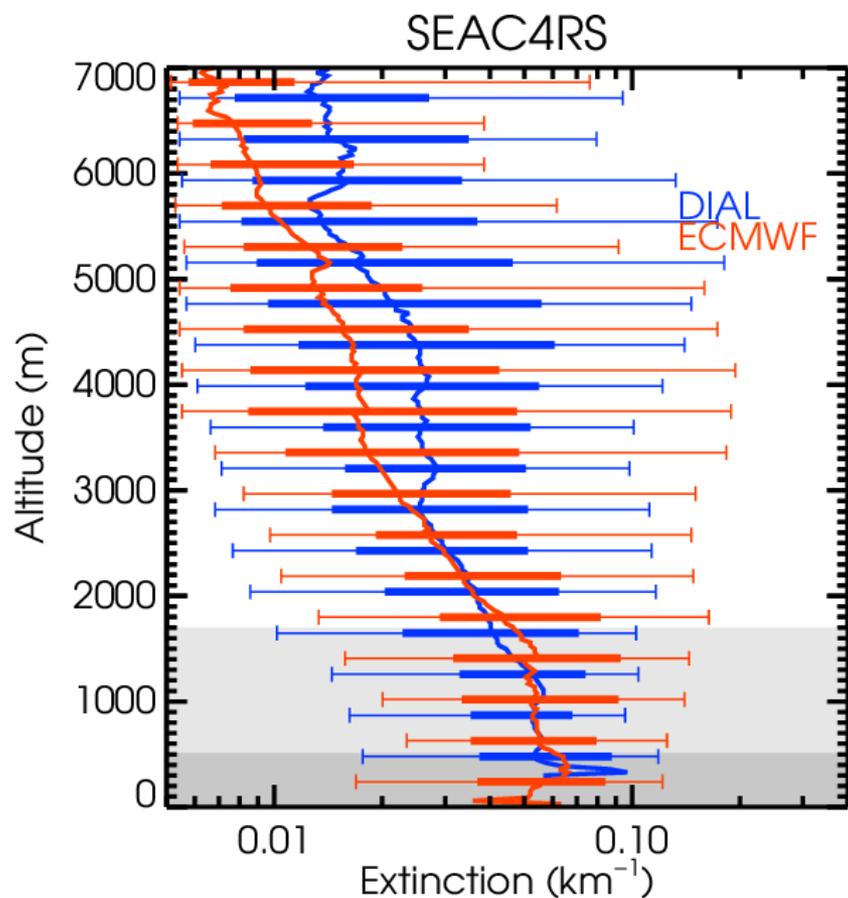
- Model resolution increased from T255 (80 km) with 60 vertical levels to T1279 (16 km) with 137 vertical levels
- Higher resolution represents smoke altitude better than assimilating MODIS AOT or using plume rise model

Evaluating the impact of higher model resolution

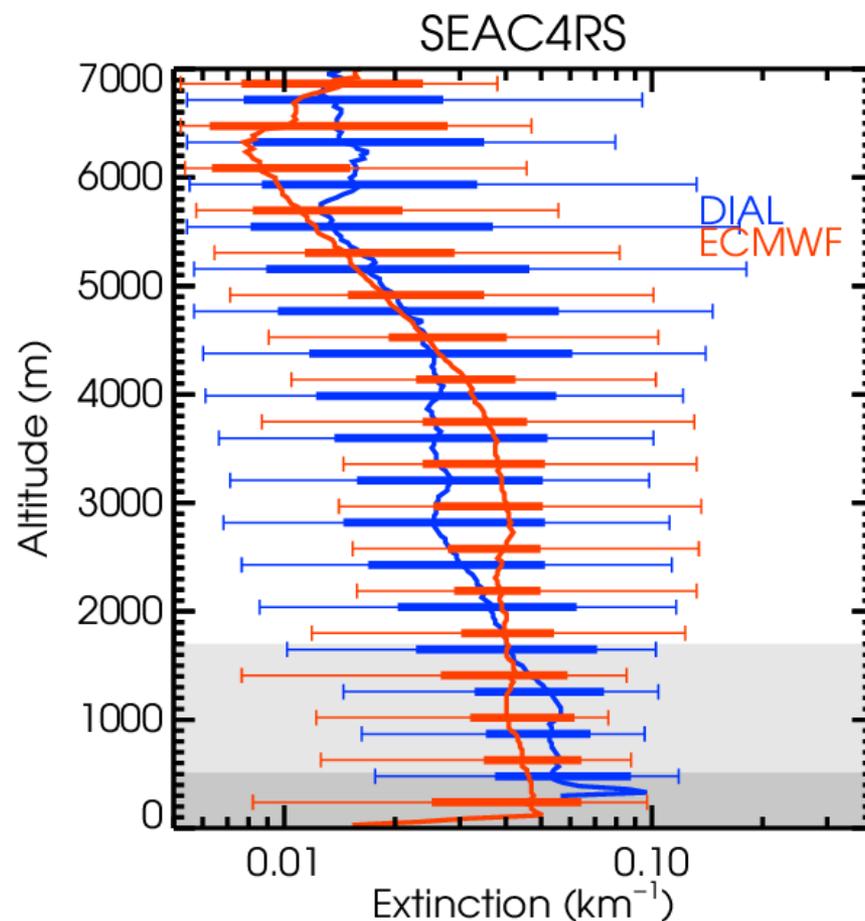


- Increasing number of vertical levels increased extinction in mid troposphere

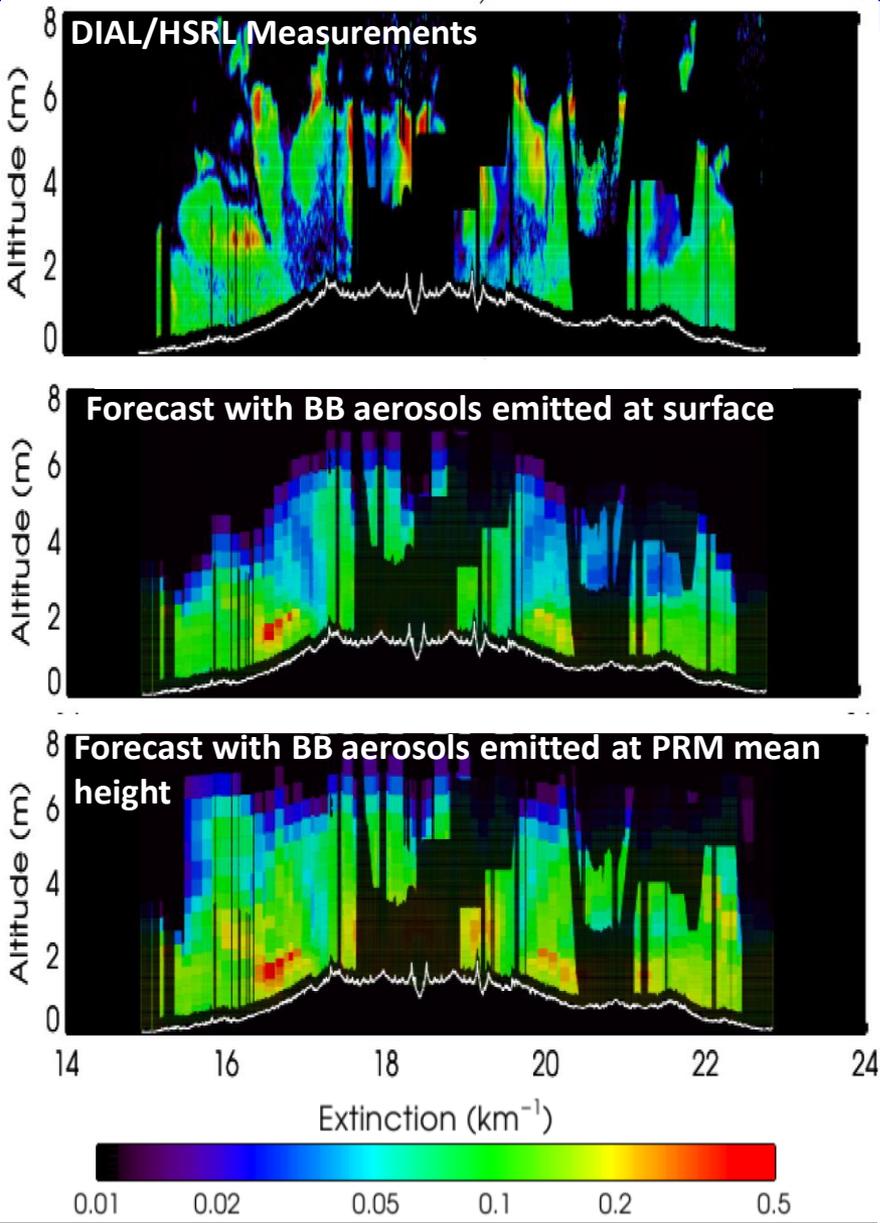
60 levels



91 levels



Evaluating the impacts of smoke injection heights computed from plume rise model



- Injection heights for smoke emissions are estimated using Plume Rise Model (based on Freitas et al., 2007)
- This plume rise model uses MODIS FRP and modelled atmospheric profiles with a shallow convection scheme to represent detrainment from fire plume
- Initial comparisons show that both aerosol extinction and AOT increase throughout the profile, not necessarily at smoke height shown in DIAL/HSRL profile

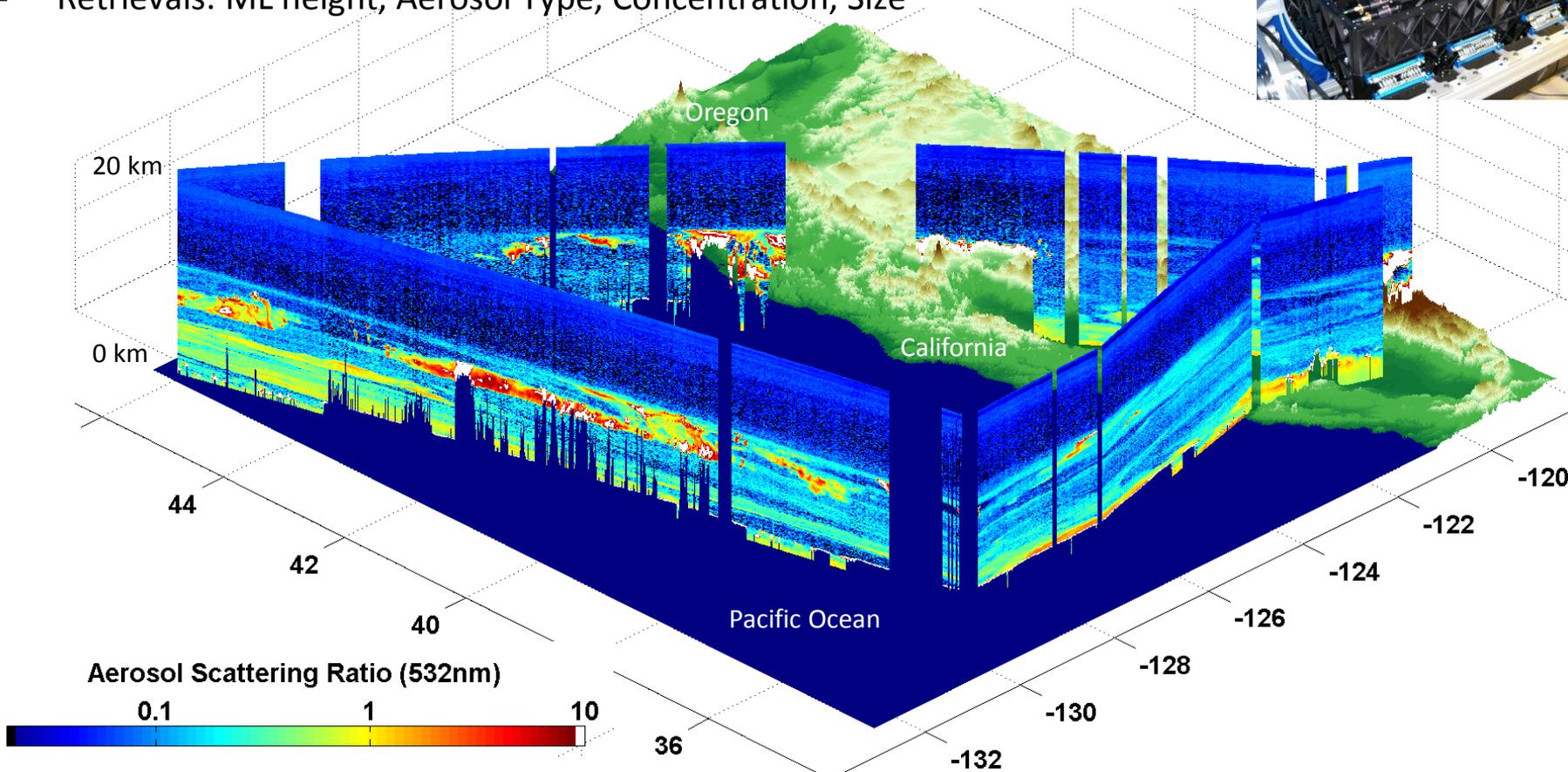
Rémy et al., ACPD, 2016

Ongoing and Future Activities

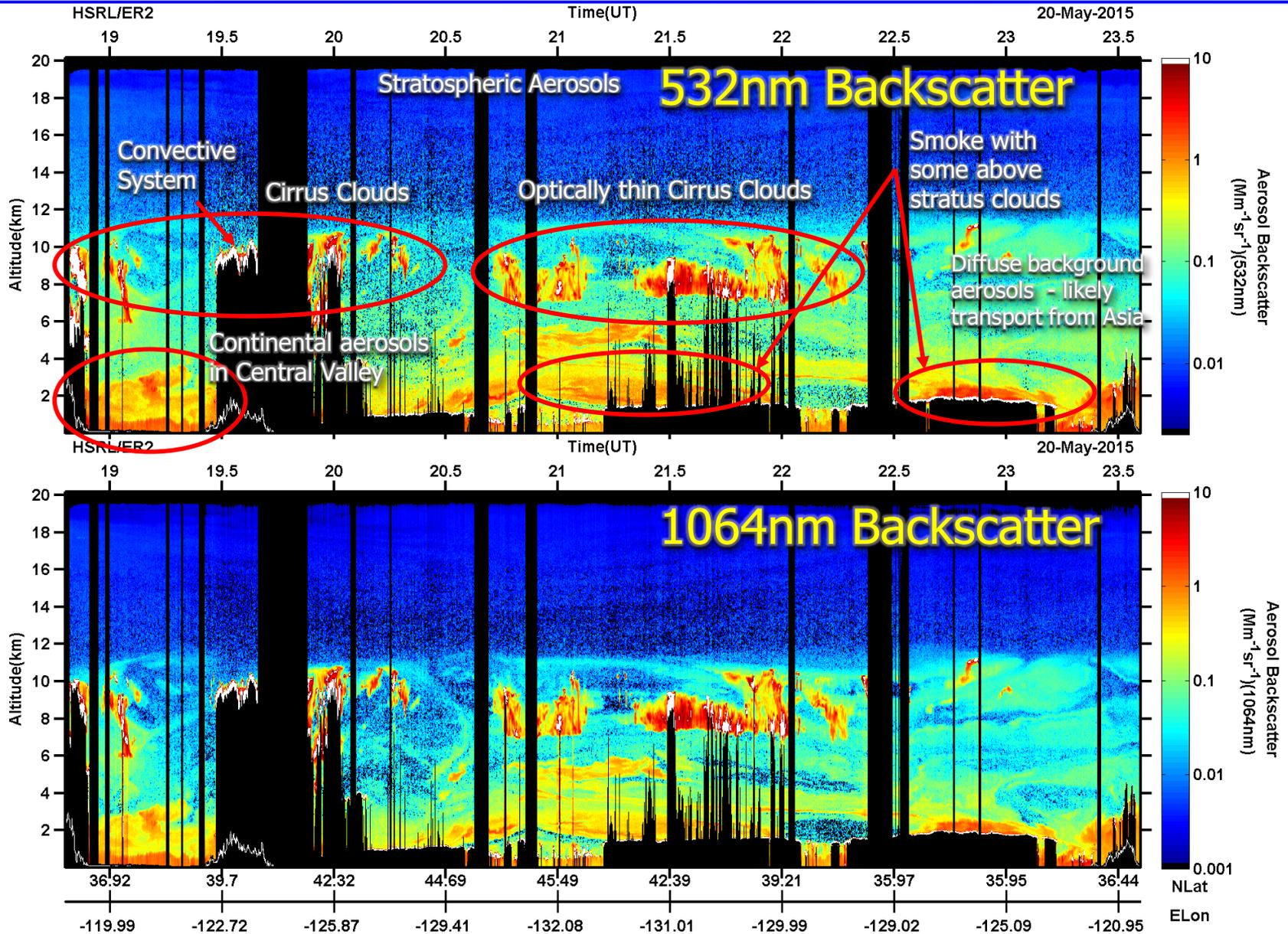
Flight demonstrations of Multi-wavelength HSRL-2 on the NASA ER-2



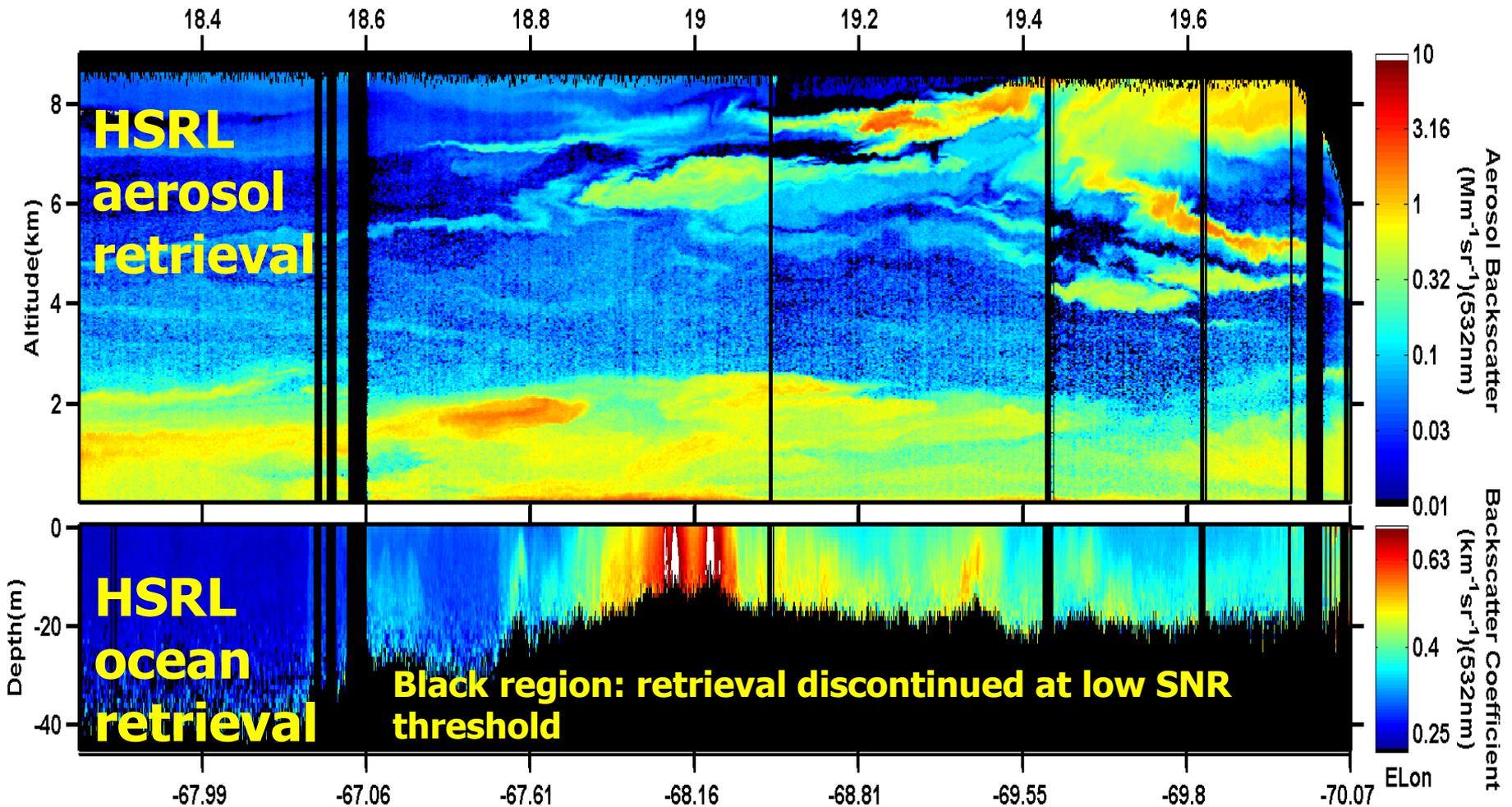
- Airborne prototype for NASA's Aerosol-Clouds-Ecosystems (ACE)
- Autonomous high-altitude (20km) ER-2 flights conducted in May 2015 and April 2016 from Armstrong Flight Research Center in California
- HSRL-2 will deploy on the ER-2 for the first ORACLES EVS-2 deployment and flights for ACE and other programs
- Measurements: Extinction*, Backscatter, Depolarization (355*,532*, 1064nm)
- Retrievals: ML height, Aerosol Type, Concentration, Size



High Spectral Resolution Lidar - ER2 Test Flights May 2015



High vertical resolution HSRL-1 enables correlating ocean productivity with aerosol



Simultaneous observation of plankton scattering and aerosol/cloud would improve understanding of biogenic contribution to CCN, cloud fraction, and cloud albedo.

- **HSRL data show $PM_{2.5}$ is better correlated with near surface extinction than AOT scaled by aerosol layer or PBL heights**
- **With exception of San Joaquin Valley, median profiles show that about only about 20-65% of AOT was within mixed layer; much of AOT was above mixed layer**
- **$PM_{2.5}$ near surface concentrations derived from HSRL multiwavelength aerosol measurements compare reasonably well with hourly values measured near the surface**
- **Median ECMWF/MACC-II and GEOS-5 model extinction profiles in agreement with median DIAL/HSRL profile**
- **Increased model resolution improves agreement with DIAL/HSRL profiles**
- **GEOS-5 simulations of aerosol depolarization are biased low – model misses local dust**
- **Both GEOS-5 and airborne HSRL data show aerosol intensive properties vary with altitude during SEAC4RS – likely due to smoke aloft**

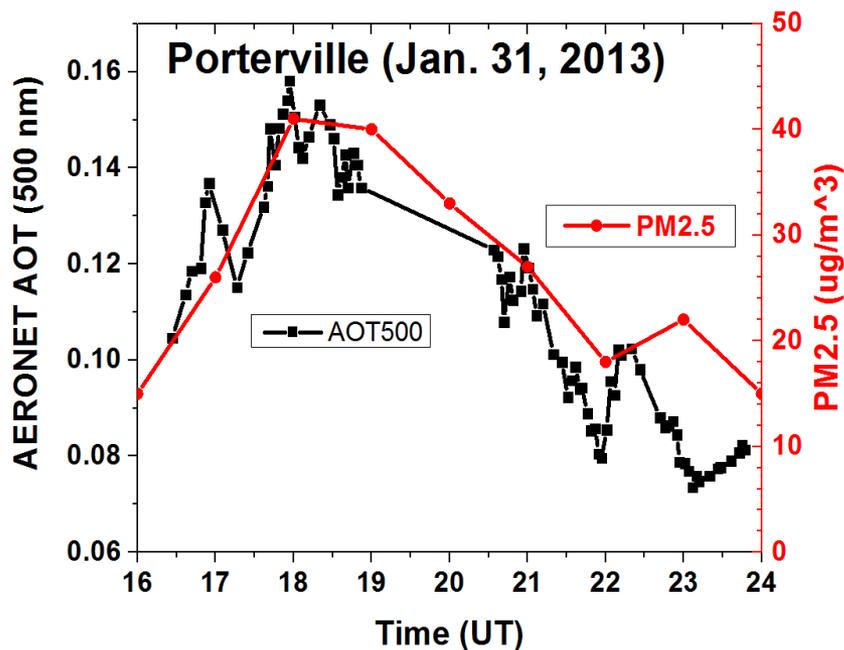
Extra Slides



Large decrease in RH over Porterville on Feb. 4 decreases correlation between $PM_{2.5}$ and AOT

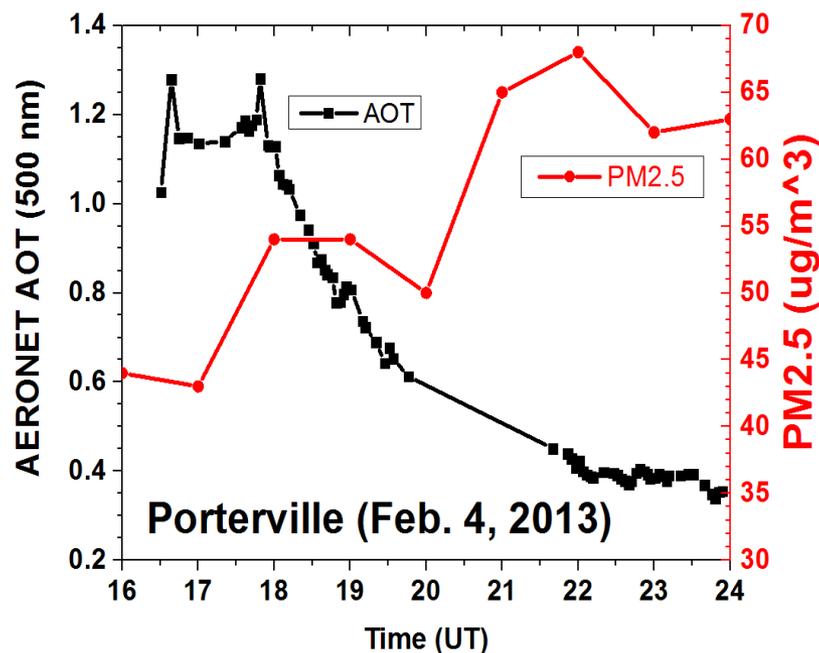
Jan. 31

- RH was generally below 70% so that $f(RH)$ was relatively low and constant
- Good correlation between AOT and $PM_{2.5}$



On Feb. 4

- High (>80-90%) RH in the morning
- Large decrease in RH led to large decrease in AOT
- Consequently, decrease in AOT was anti-correlated with increase in $PM_{2.5}$



GEOS-5 Atmospheric Data Assimilation System



- GEOS-5 Earth Modeling System, GOCART aerosol module
- Five non-interactive species - dust, sea salt, BC, OC, sulfate
- Convective and large scale wet removal
- Dry deposition and sedimentation
- Optics based on OPAC model (Nonspherical Dust) from Colarco; Kim
- Fire emissions – Quick Fire Emission Dataset (QFED)
 - Based on MODIS Fire Radiative Power
 - Emission factors tuned using MODIS AOT
 - Daily mean emissions
- Aerosol Data Assimilation
 - Terra/Aqua MODIS AOT
 - MISR AOT over bright surfaces
- Resolution
 - Horizontal: 25 km
 - Vertical: 72 layers
- PBL heights defined when diffusion coefficient falls below threshold
- **GEOS-5 3-hourly results from SEAC4RS reanalysis are examined here**

dust	wind and topographic source, 5 mass bins
sea salt	wind driven source, 5 mass bins
black carbon	anthropogenic and wildfire source, mass hydrophobic and hydrophilic
organic carbon	anthropogenic, biogenic, and wildfire source, mass hydrophobic and hydrophilic
sulfate	anthropogenic and wildfire source of SO ₂ , oxidation to SO ₄ mass

ECMWF/MACC-III Model



- Monitoring Atmospheric Composition and Climate-Interim Implementation (MACC-III) Model
 - Provides information regarding air quality, global atmospheric composition, climate forcing, solar energy
 - Consumers include WMO, EPA and European Centers, weather services, solar irradiance forecast groups, field campaigns
- Aerosol model has components for dust, sea salt, organic matter, black carbon, sulfate
- Eleven prognostic aerosol variables and one for SO₂
- Aerosol sources taken from
 - Global Fire Assimilation System (GFAS) (Kaiser et al., Biogeosciences, 2012)
 - Sea salt and dust – emissions computed online in aerosol model using met parameters
 - BC, SO₂, OM - Emission Database for Global Atmospheric Research (EDGAR)
- Resolution
 - Horizontal: T255 (~80 km)
 - Vertical: 60 layers
- Aerosol Data Assimilation
 - Terra/Aqua MODIS AOT
 - Working towards assimilation of CALIOP aerosol profiles
- MACC-III 3-hourly results from a series of experiments are examined here
- SEAC4RS DIAL/HSRL data used to examine impacts of:
 - Assimilation of CALIOP data
 - Increased model resolution
 - Plume rise model impact on smoke injection heights

Comparison of Mixed Layer Heights from HSRL-2 and GEOS-5 during SEAC4RS



- DIAL/HSRL mixed layer heights from aerosol backscatter gradients
- GEOS-5 boundary (mixed) layer heights from thermal diffusivity and aerosol backscatter gradients were about 500-600 m higher than those derived from HSRL-2 and DIAL/HSRL

