Using Airborne HSRL Measurements to Evaluate and Understand Aerosol Models

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Motivation and Objectives

Motivation:

- Global forecasting centers (e.g. ECMWF, NASA, NRL, NOAA, JMA) are increasingly using lidar (e.g. CALIOP, CATS) data to constrain aerosol vertical distributions
- Aerosol model verification using independent and calibrated lidar data is of great interest

Objectives:

- Examine aerosol model products using calibrated aerosol profiles acquired by the NASA Langley Research Center (LaRC) airborne High Spectral Resolution Lidars (HSRL-1, HSRL-2, DIAL/HSRL)
  - Mixed Layer heights
  - Aerosol optical thickness (AOT)
  - Aerosol extinction profiles
  - Aerosol intensive parameters (lidar ratio, color ratios, depolarization)
  - Aerosol types
  - Retrievals of effective radius, concentration, $PM_{2.5}$

Airborne HSRL Measurements

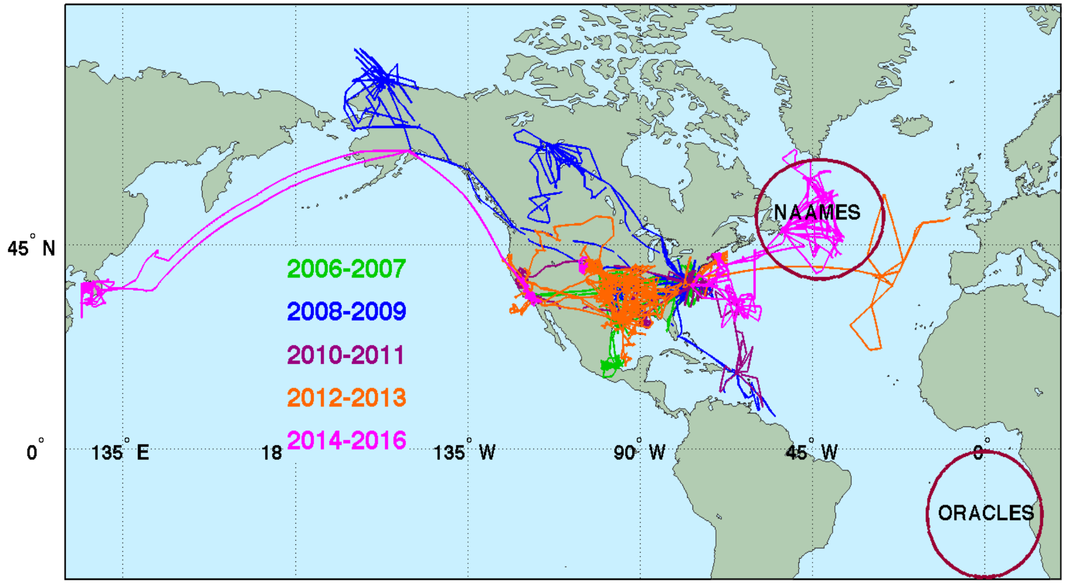
Currently, three NASA LaRC Airborne HSRL systems provide aerosol profile measurements

- All systems use HSRL technique to independently measure calibrated aerosol backscatter and extinction profiles (and derive layer AOT)
- Common aerosol data products
  - Backscatter Profiles (532, 1064 nm)
  - Depolarization Profiles (532, 1064 nm)
  - Extinction Profiles (532 nm)
  - AOT Profiles (532 nm)
  - Qualitative aerosol classification
  - Mixed Layer heights
- DIAL/HSRL
  - Long (~30 year) heritage of providing ozone and aerosol measurements; HSRL operations began in 2012
  - Long-range operations from NASA DC-8
  - Provides simultaneous aerosol and ozone profiles above and below DC-8

- HSRL-1
  - Began operations in 2006
  - Operations typically from LaRC King Air, P-3, or C-130
  - Modified to also provide sub-surface ocean profiling

- HSRL-2
  - Began operations in 2012
  - Includes additional backscatter, extinction, and depolarization profiles at 355 nm and ozone
  - Retrievals of aerosol size, concentration
  - Demonstrated operations from NASA ER-2

NASA LaRC Airborne HSRL Measurement Locations



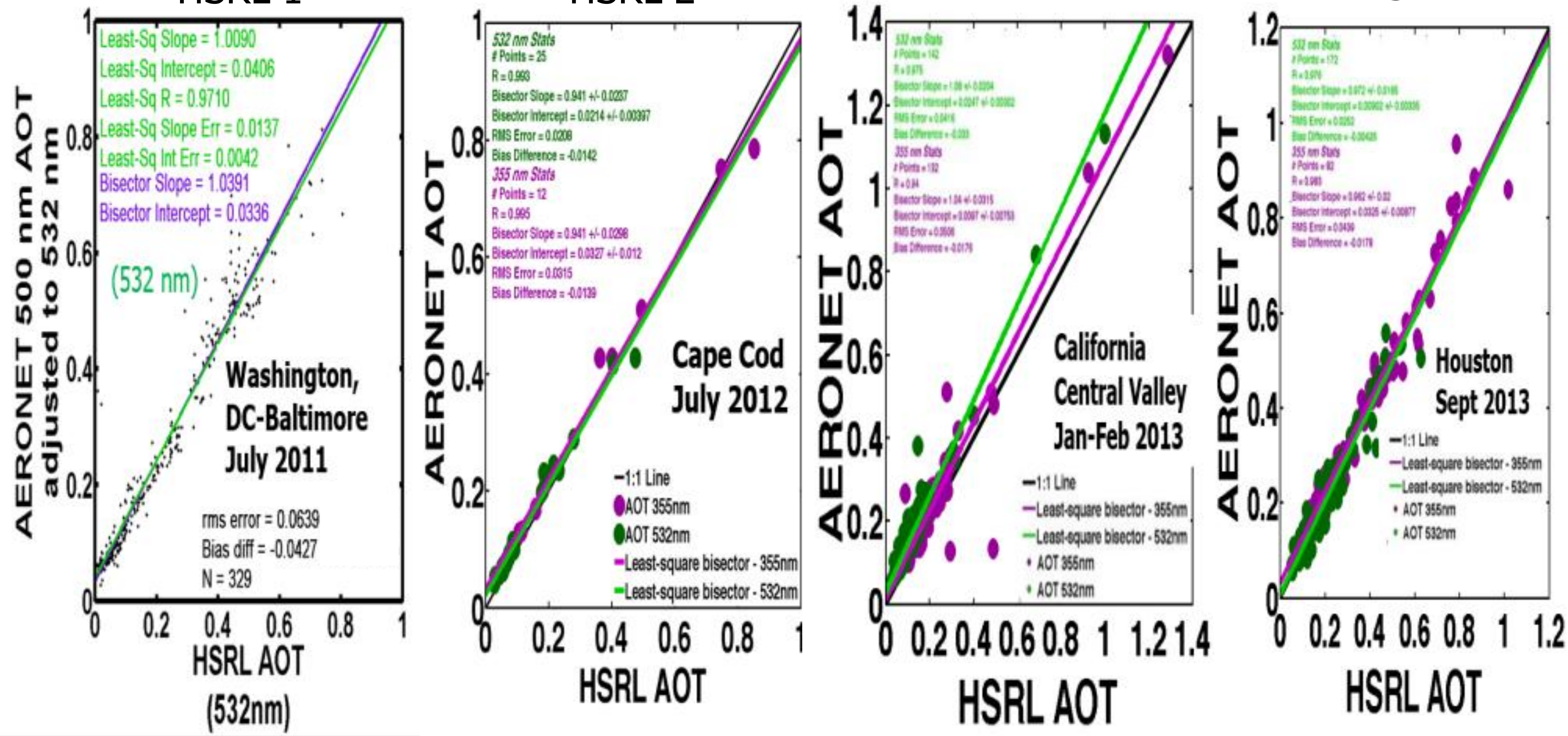
- Airborne HSRL measurements acquired during more than 450 flights since 2006
- HSRL-1 operations began 2006
- HSRL-2 operations began 2012
- DIAL/HSRL operations began 2012
- Additional flights planned over North Atlantic (2017-2018) and South Atlantic (2016-2018)

Field Mission	Dates	Location	Instrument	Sponsor [1]
MILAGRO/INTEX	3/2006	Mexico City	HSRL-1	DOE
CALIPSO Validation	5/2006-8/2006	SE US	HSRL-1	NASA
TexAQS/GOMACCS	9/2006	Houston	HSRL-1	DOE
San Joaquin Valley	2/2007	California	HSRL-1	EPA
CHAPS/CLASIC	6/2007	Oklahoma	HSRL-1	DOE
CATZ CALIPSO Val.	1/2007, 8/2007	Eastern US	HSRL-1	NASA
Caribbean 1	1/2008-2/2008	Caribbean	HSRL-1	NASA
ARCTAS Spring	4/2008	Alaska	HSRL-1	NASA
ARCTAS Summer	6/2008-7/2008	NW Canada	HSRL-1	NASA
Birmingham	9/2008-10/2008	Alabama	HSRL-1	EPA
CALIPSO Validation	1/2009, 4/2009	Eastern US	HSRL-1	NASA
RACORO	6/2009	Oklahoma	HSRL-1	DOE
Ocean Subsurface	9/2009	East Coast	HSRL-1	NASA
CALIPSO Validation	4/2010	Eastern US	HSRL-1	NASA
CALIPSO Gulf Oil Spill	5/2010, 7/2010	Gulf of Mexico	HSRL-1	NASA
CalNEX	5/2010	Los Angeles	HSRL-1	DOE/NASA
CARES	6/2010	Sacramento	HSRL-1	DOE/NASA
Caribbean 2	8/2010	Caribbean	HSRL-1	NASA
DISCOVER-AQ	7/2011	DC-Baltimore	HSRL-1	NASA
EPA	8/2011	SE Virginia	HSRL-1	EPA
DEVOTE	10/2011	SE US	HSRL-1	NASA
CALIPSO Validation	3/2012	Eastern US	HSRL-1	NASA
DC3	5/2012-6/2012	Central US	DIAL/HSRL	NASA
TCAP	7/2012	Cape Cod	HSRL-2	DOE
Azores	10/2012	Azores	HSRL-1	NASA
DISCOVER-AQ	1/2013-2/2013	Central CA	HSRL-2	NASA
SEAC4RS	8/2013-9/2013	CONUS	DIAL/HSRL	NASA
DISCOVER-AQ	9/2013	Houston	HSRL-2	NASA
CALIPSO Validation	6/2014	Eastern US	HSRL-1	NASA
SABOR	7/2014-8/2014	Atlantic Ocean	HSRL-1	NASA
DISCOVER-AQ	7/2014-8/2014	Denver	HSRL-2	NASA
NAAMES	11/2015	W North Atlantic	HSRL-1	NASA
KORUS-AQ	5/2016-6/2016	South Korea	DIAL/HSRL	NASA
NAAMES	5/2016-6/2016	W North Atlantic	HSRL-1	NASA
ORACLES	8/2016-9/2016	Namibia/ S East Atlantic	HSRL-2	NASA
ORACLES	8/2017	Namibia/ S East Atlantic	HSRL-2	NASA
NAAMES	9/2017-10/2017	W North Atlantic	HSRL-1	NASA
NAAMES	3/2018-4/2018	W North Atlantic	HSRL-1	NASA
ORACLES	11/2018	Namibia/ S East Atlantic	HSRL-2	NASA
CAMPEX	2018	?	?	?
FIRE-X	2018	?	?	?

Coincident HSRL and AERONET measurements of AOT compare well

- HSRL 0-7 km layer AOT values were compared with column AOT (355 and 532 nm) values from AERONET stations when HSRL was within 2.5 km and 10 minutes of site
  - (532 nm) Slope 0.94-1.08, Intercept 0.01-0.03, R~0.98-0.99
  - (355 nm) Slope 0.94-1.04, Intercept 0.03, R~0.98-0.99
- Bias differences ~ 0.01-0.04

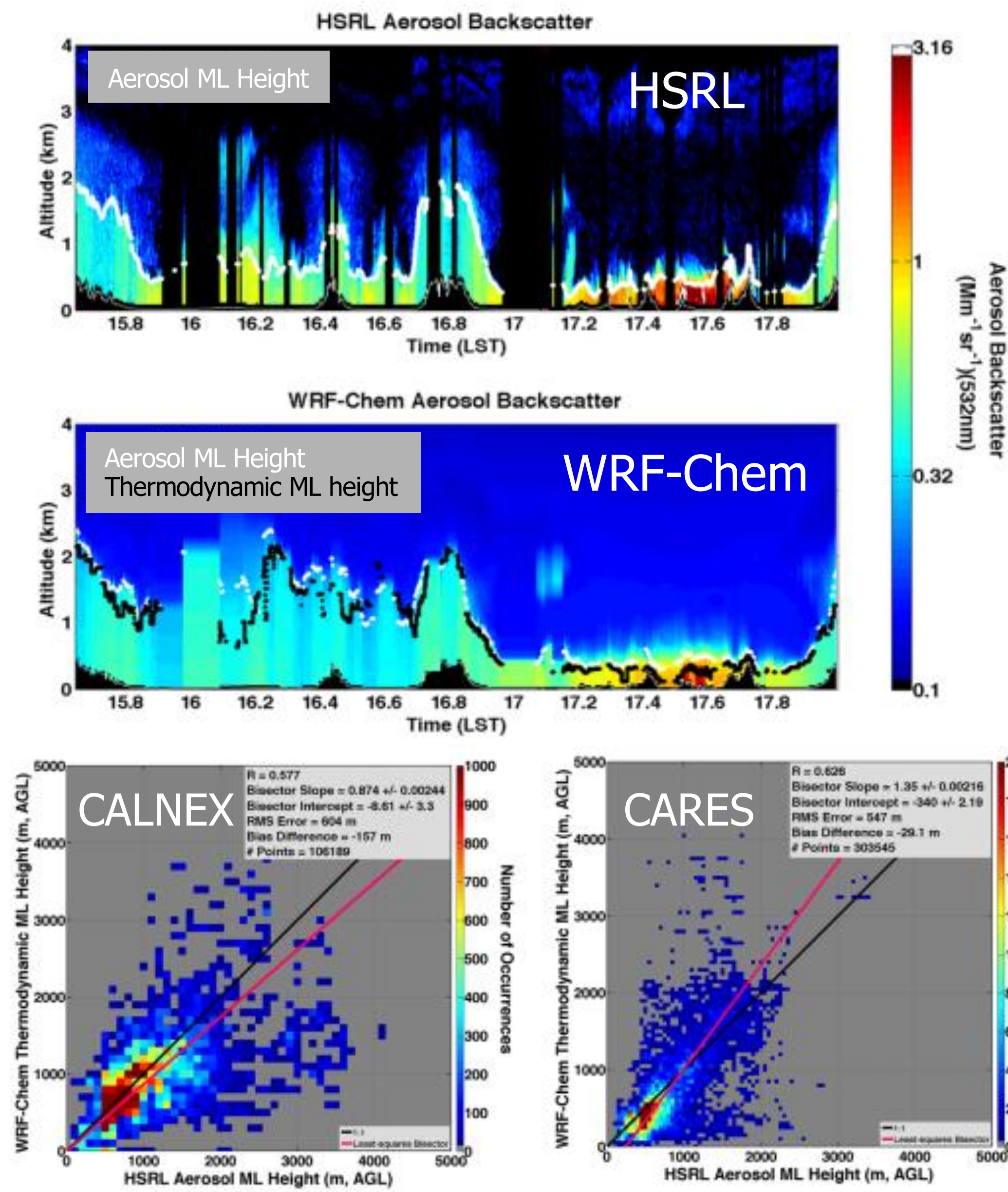
HSRL-1 | HSRL-2 | HSRL-2 | HSRL-2



Mixed Layer Heights and Median Aerosol Profiles

Comparison of Mixed Layer Heights from HSRL-1 and WRF-Chem during CALNEX and CARES

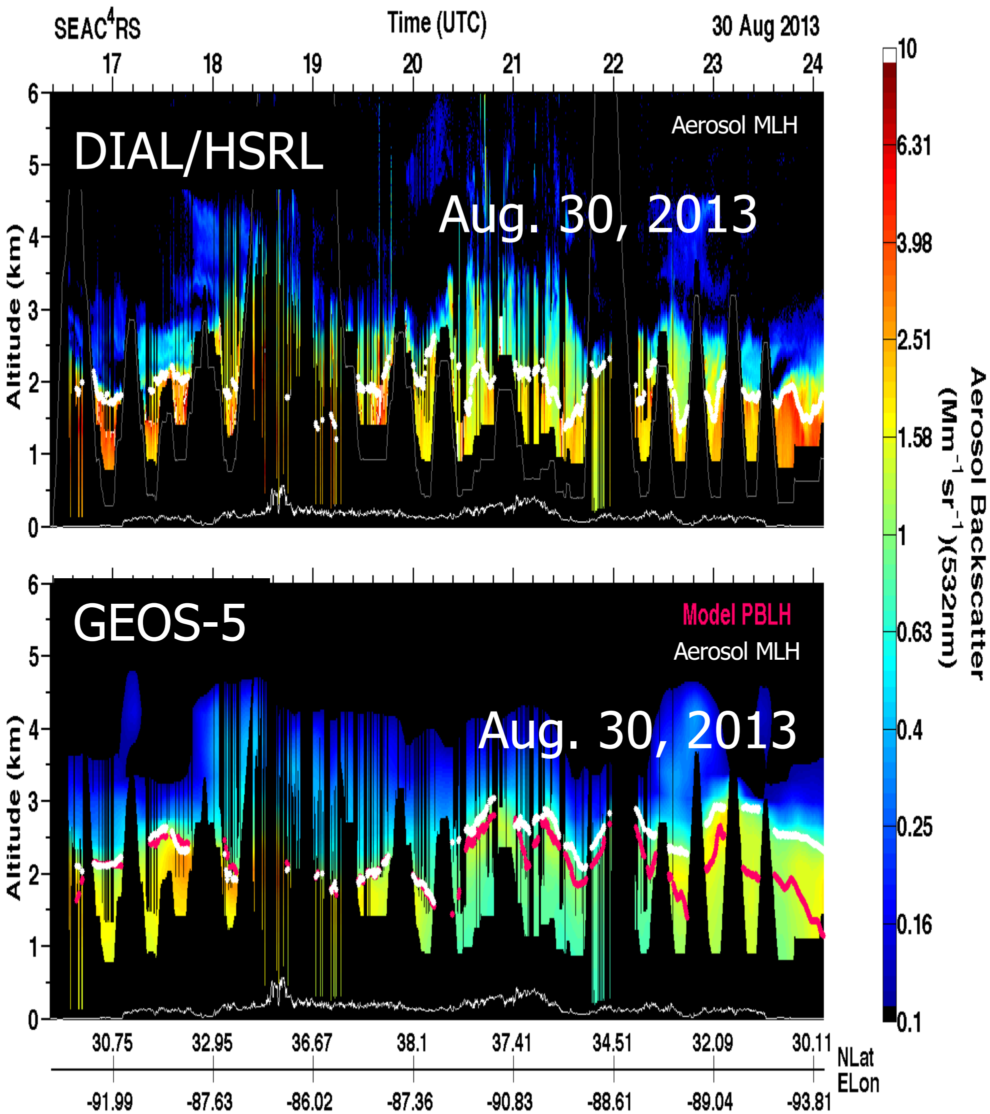
- Mixed Layer (ML) heights derived from daytime-only cloud-screened aerosol backscatter profiles measured by HSRL
- Technique uses a Haar wavelet covariance transform with multiple wavelet dilations to identify sharp gradients in aerosol backscatter at the top of aerosol layers (adapted from Brooks, JAOT, 2003)
- Automated HSRL algorithm chooses ML from among aerosol gradients in HSRL backscatter profiles with input from manual inspection where necessary
- ML heights computed for 15 science campaigns (212 flights) since 2006
- WRF-Chem had low (~150 m) bias in Los Angeles region (CALNEX); smaller bias (~30 m) in flatter central Valley (CARES)

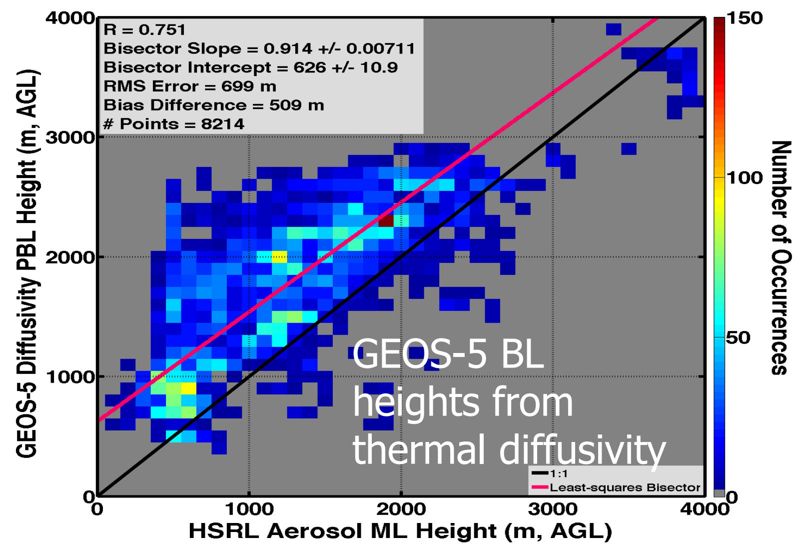


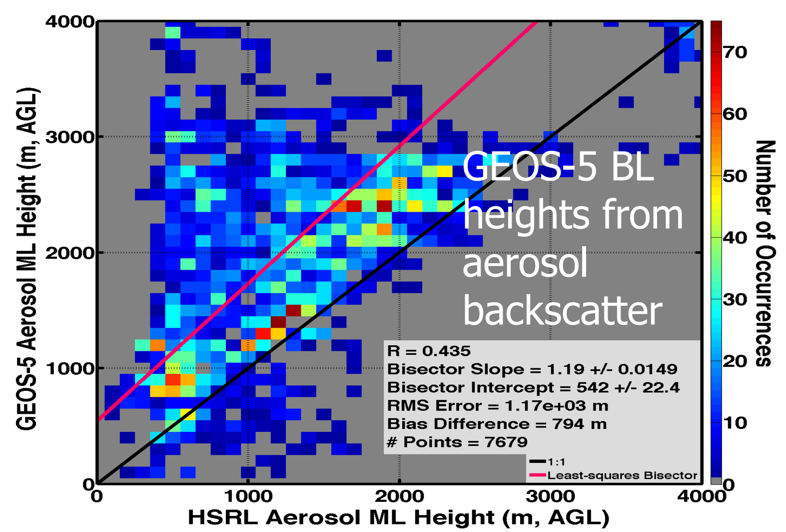
Scarino et al., 2014, ACP

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

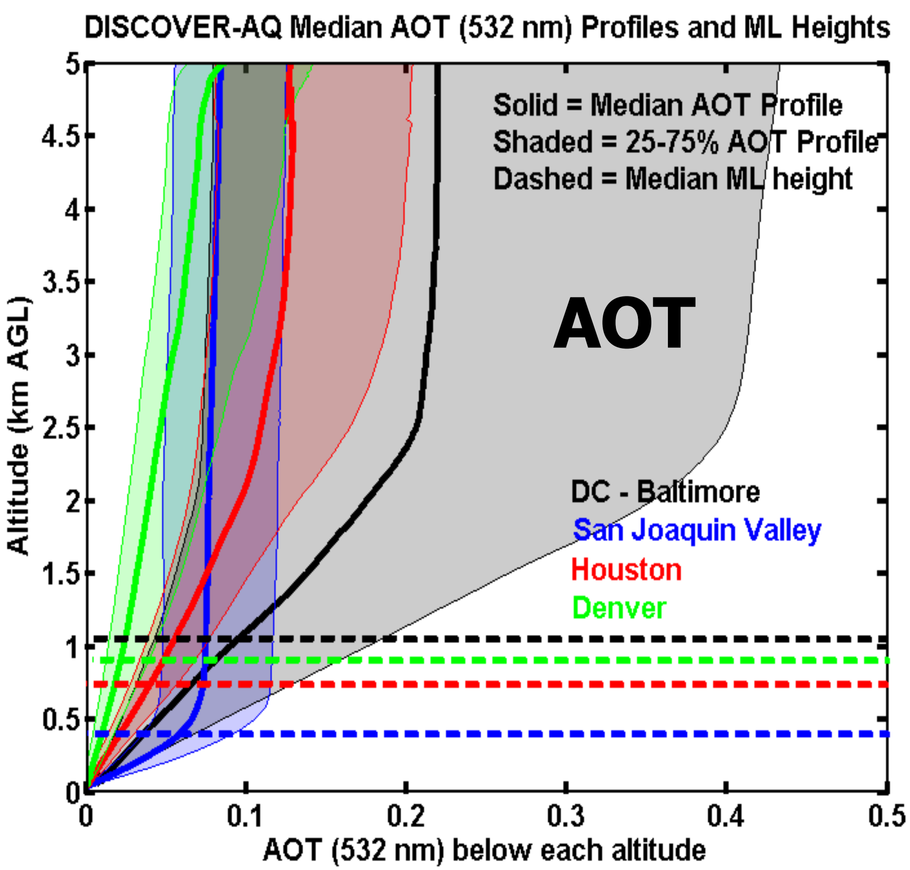
- DIAL/HSRL boundary layer heights from aerosol backscatter gradients
- GEOS-5 boundary layer heights from thermal diffusivity <u>and</u> aerosol backscatter gradients were about 500-600 m higher than those derived from HSRL-2 and DIAL/HSRL

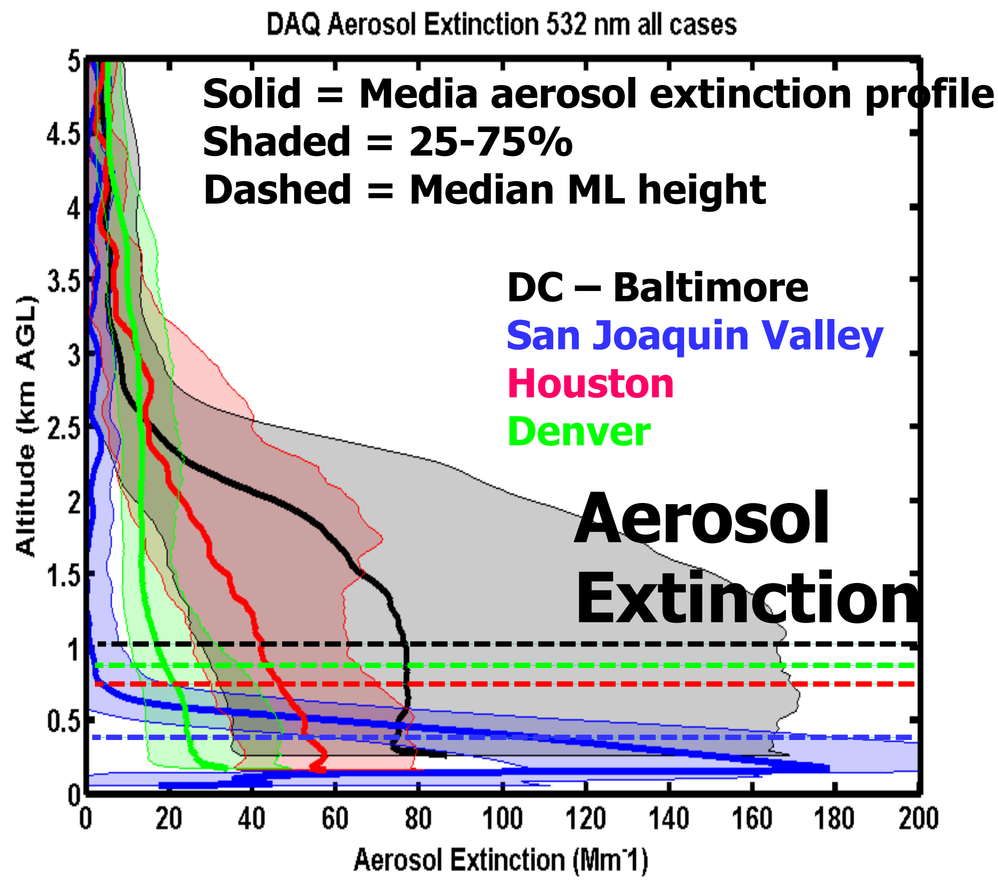






HSRL measurements show much of AOT is often above the daytime mixed layer





- 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 – ECMWF Comparisons

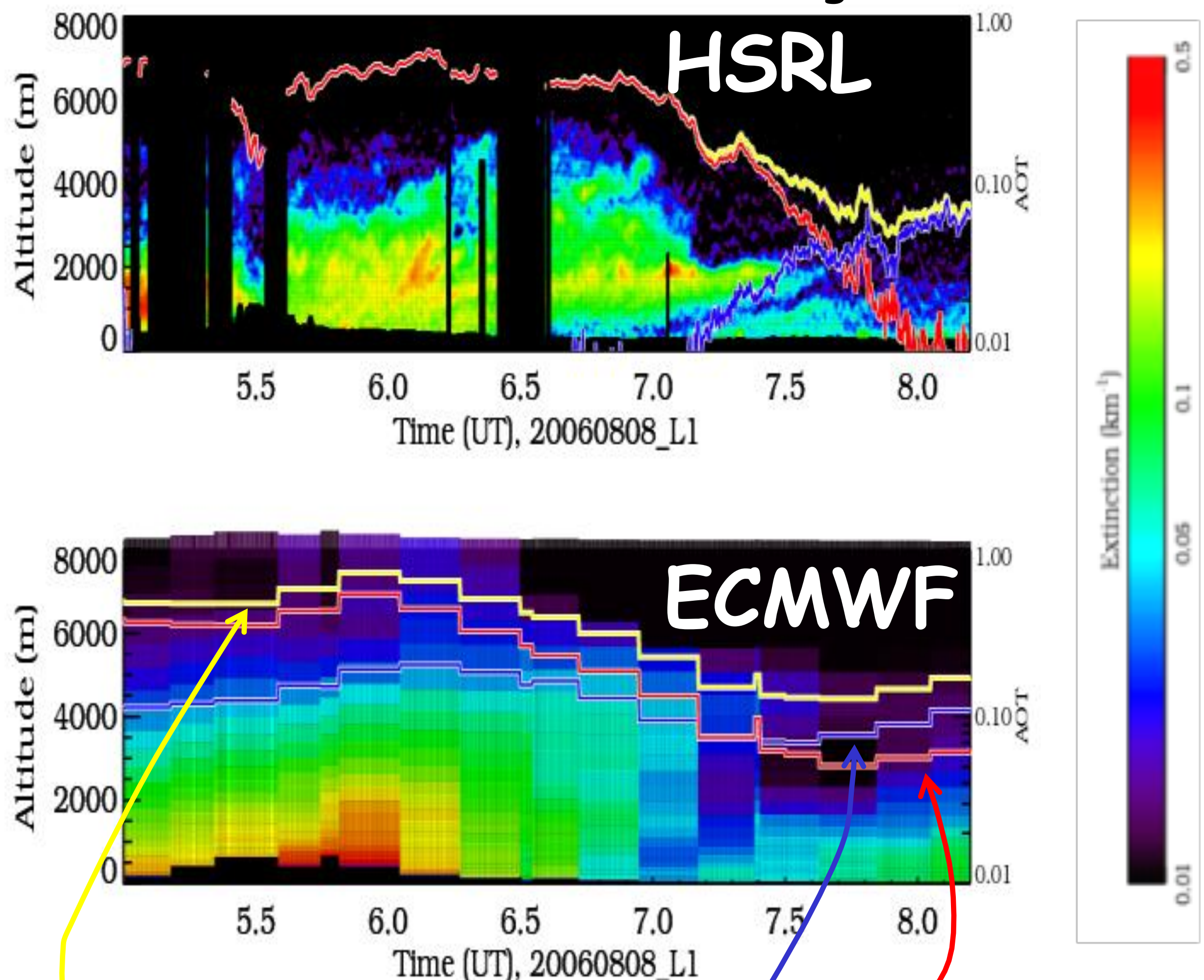
HSRL and ECMWF Model Comparison Methodology

ECMWF model results and HSRL measurements were compared along the King Air flight tracks for 17 field missions conducted over North America since 2006

Comparisons include:

- **AOT in the 0-7 km column**
- **Aerosol extinction profiles**
- **Fraction of AOT and extinction due to natural (ice, pure dust, marine) and anthropogenic (polluted marine, urban, smoke, fresh smoke) aerosols**
- **PBL height (mixed layer height from HSRL used as proxy for PBL height)**
- **Fraction of AOT within the PBL**

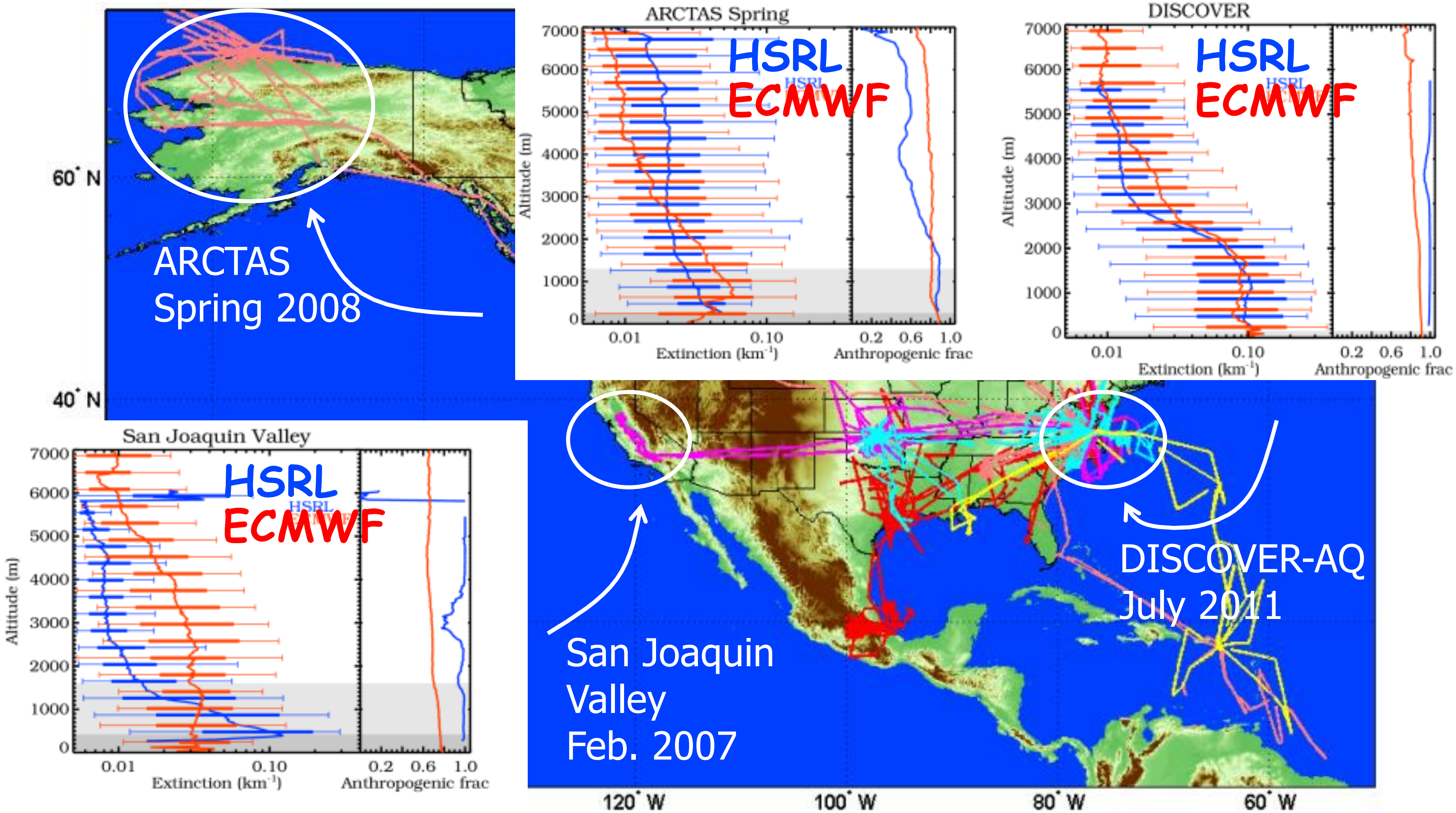
Aerosol Extinction and AOT August 8, 2006



Total (yellow), natural (blue), anthropogenic (red) AOT values are shown

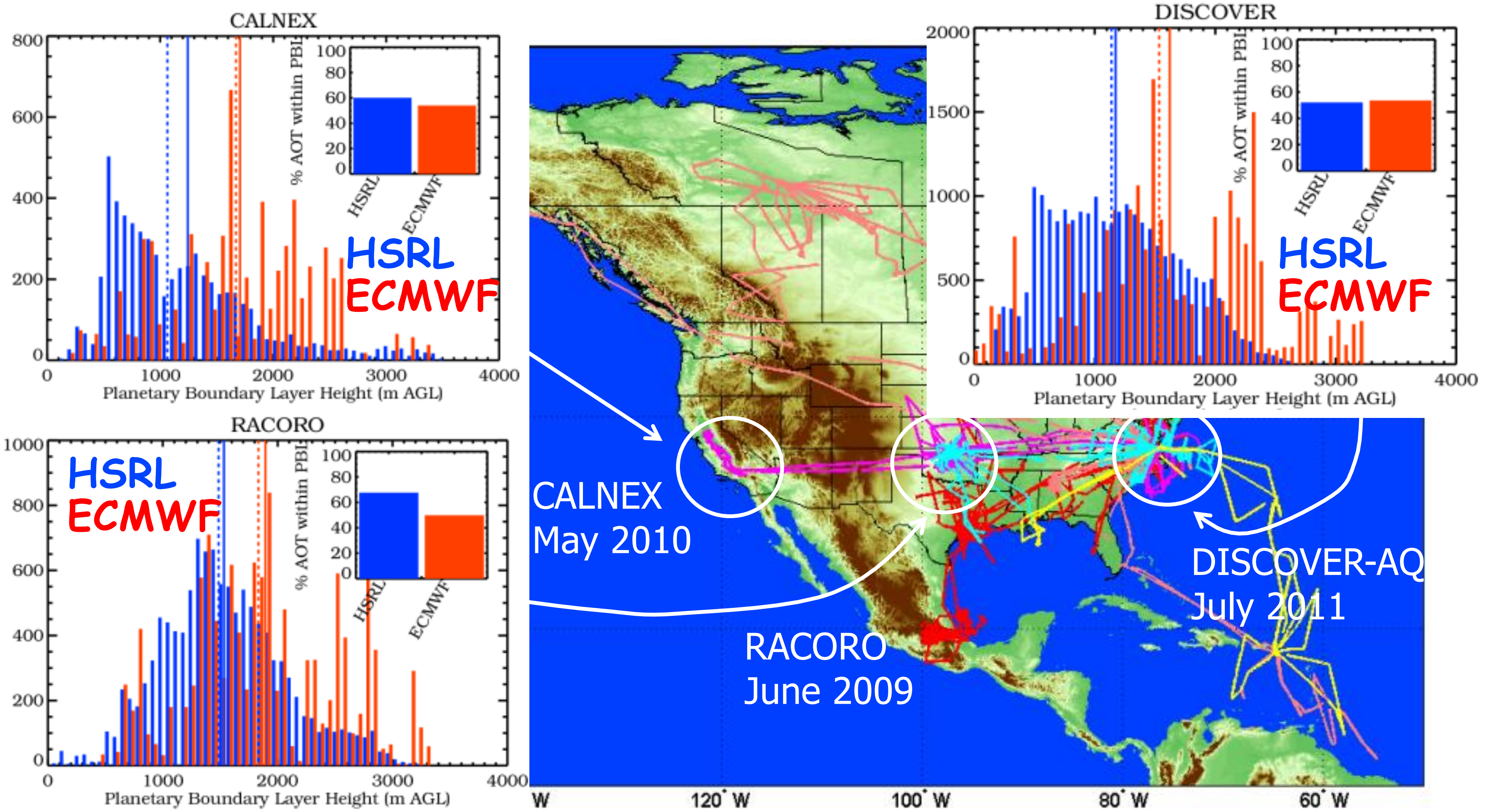
Aerosol Extinction Profile Comparison

- Considerable variability in aerosol extinction profile comparisons
- Best agreement found in the PBL
- ECMWF often has higher extinction in free troposphere, especially over the western USA

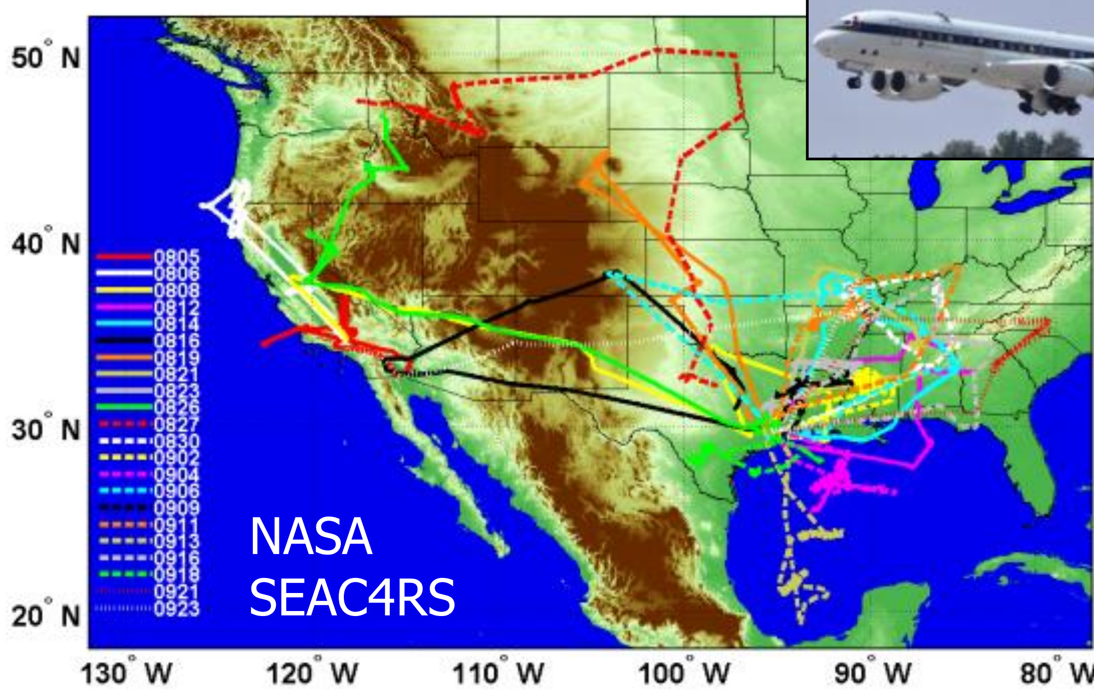


PBL Height Comparisons

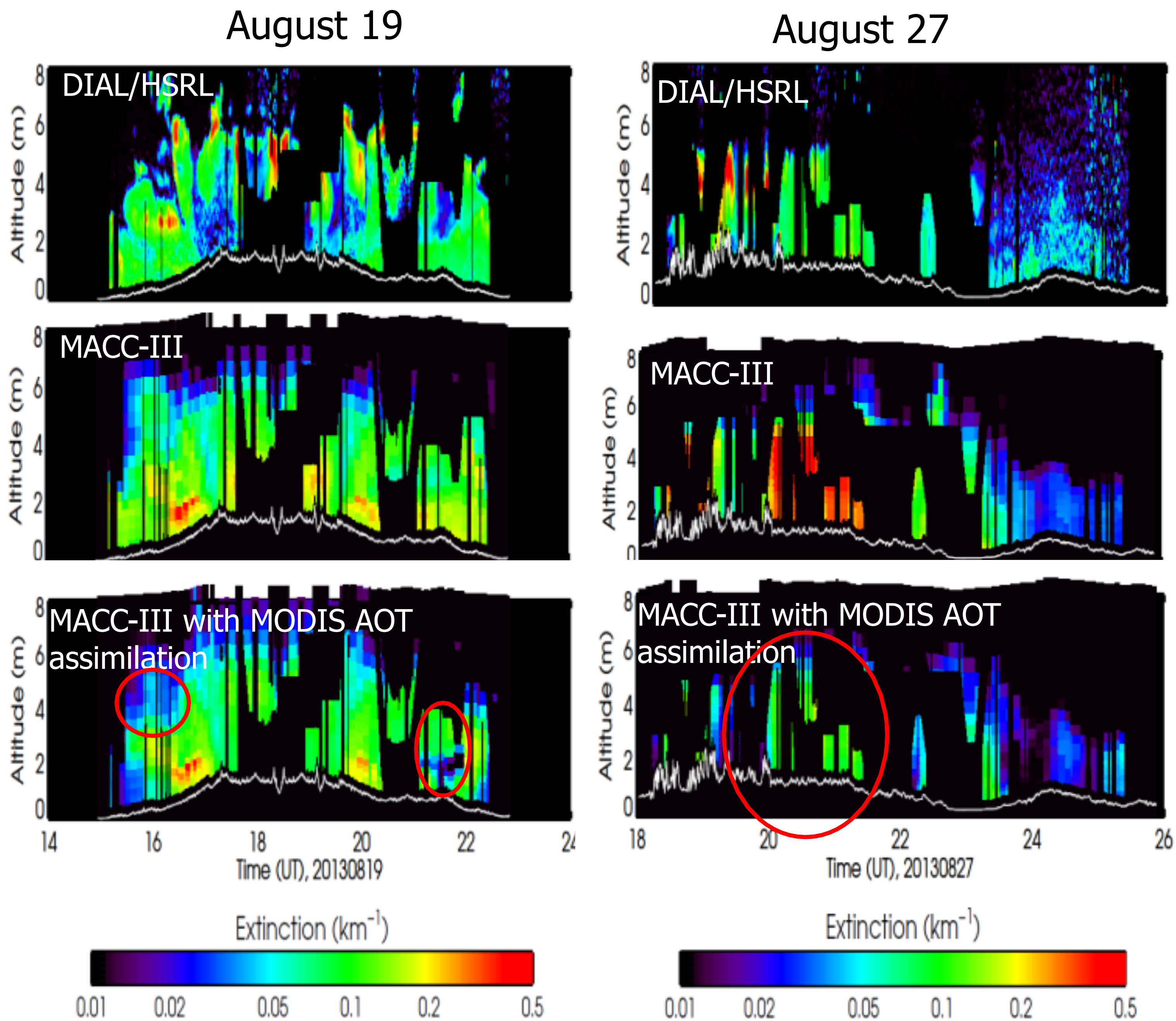
- Overall, ECMWF PBL heights are generally about 100-200 m higher than HSRL ML heights
- Fraction of AOT within the PBL is about the same



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

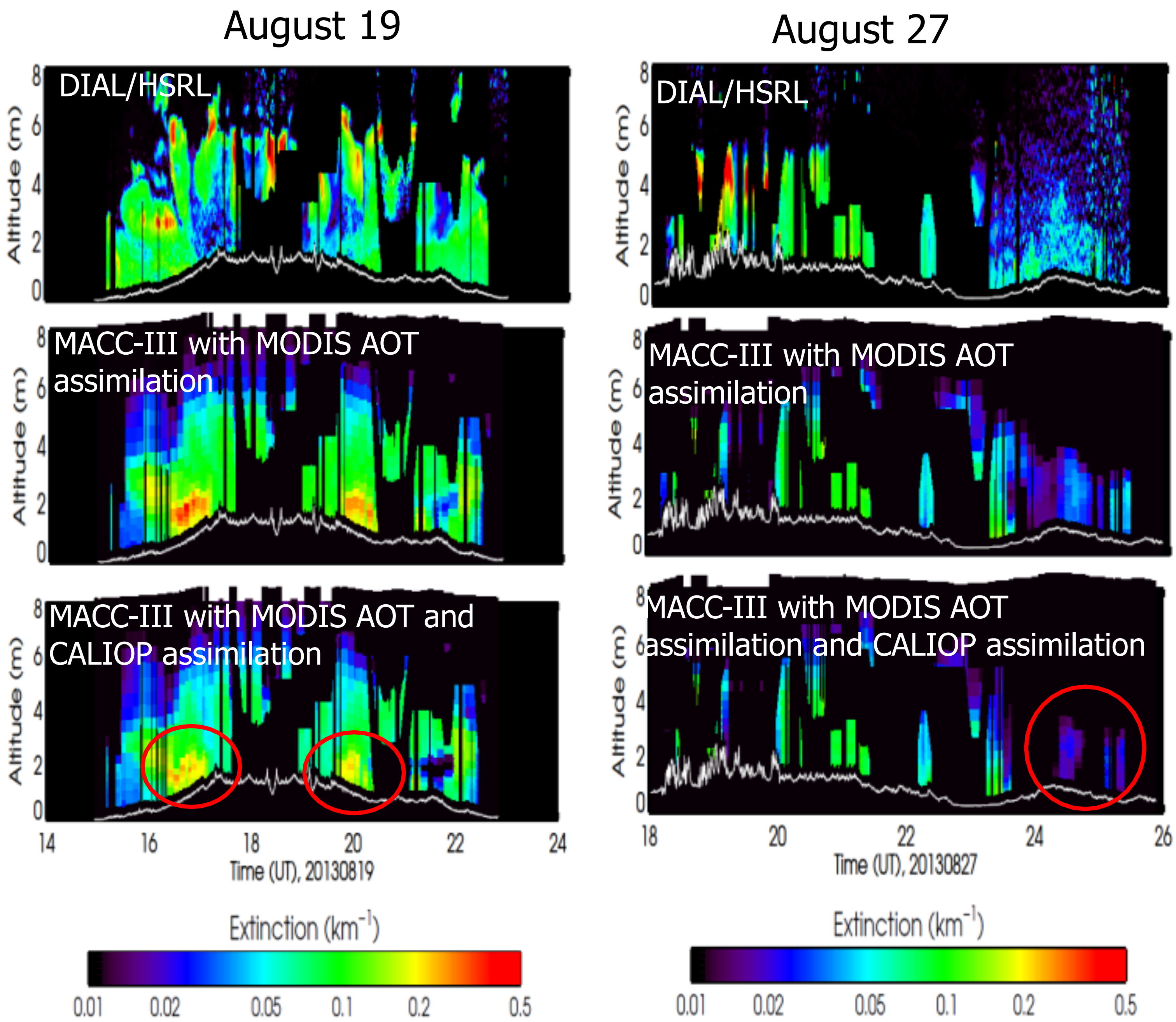


Evaluating the impacts of MODIS AOT assimilation



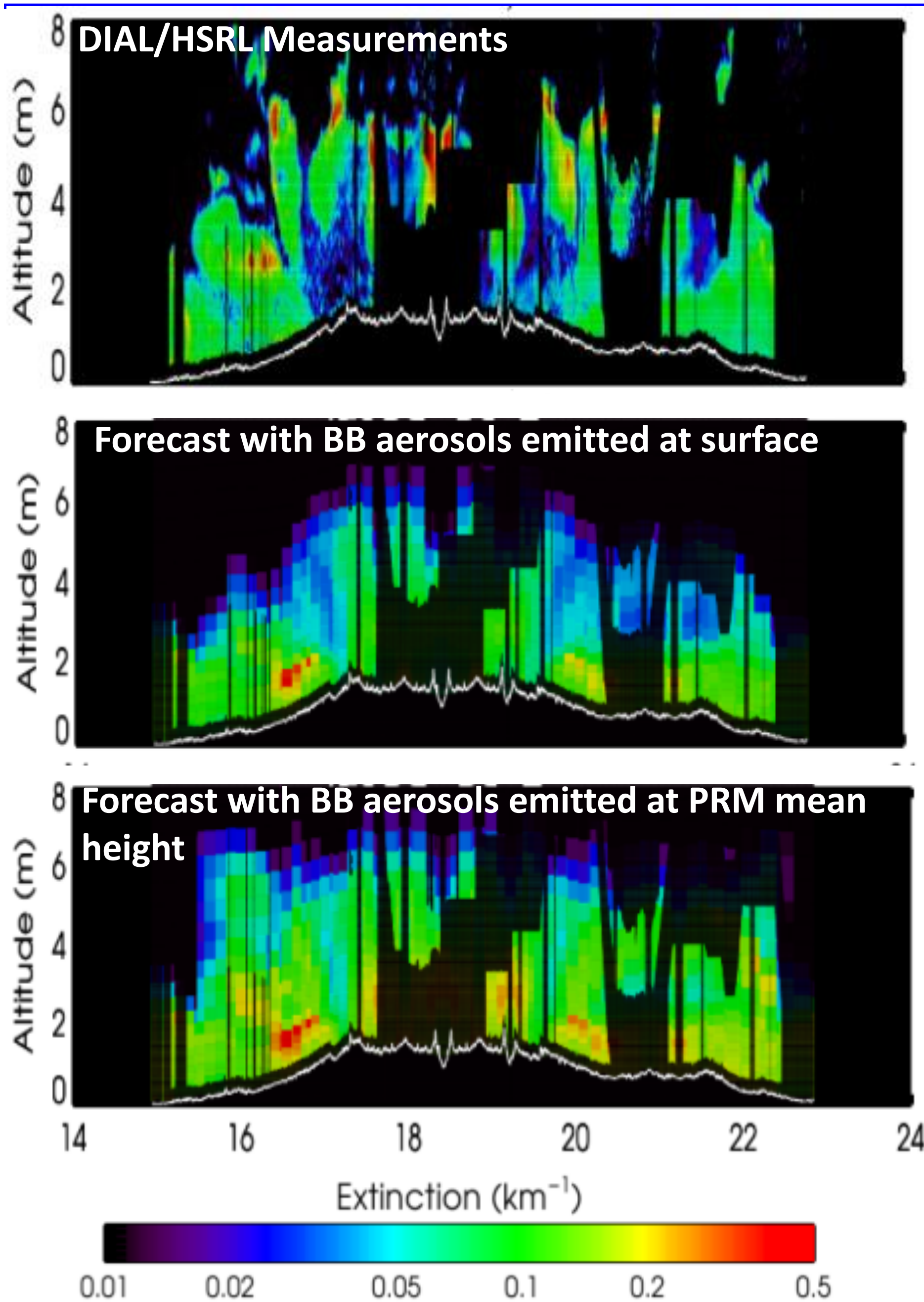
- Aug. 19 case had extensive smoke layers from CA, OR, ID fires
- Aug. 27 had Rim Fire smoke
- Assimilation of MODIS AOT reduces aerosol extinction profiles in some sections of these flights
- Reductions in aerosol extinction vary with altitude

Evaluating the impacts of CALIOP profile assimilation



- Assimilation of CALIOP profiles slightly reduces extinction profiles in some locations; largest extinction values remain near surface
- Depending on location, these reductions can improve or worsen agreement with HSRL

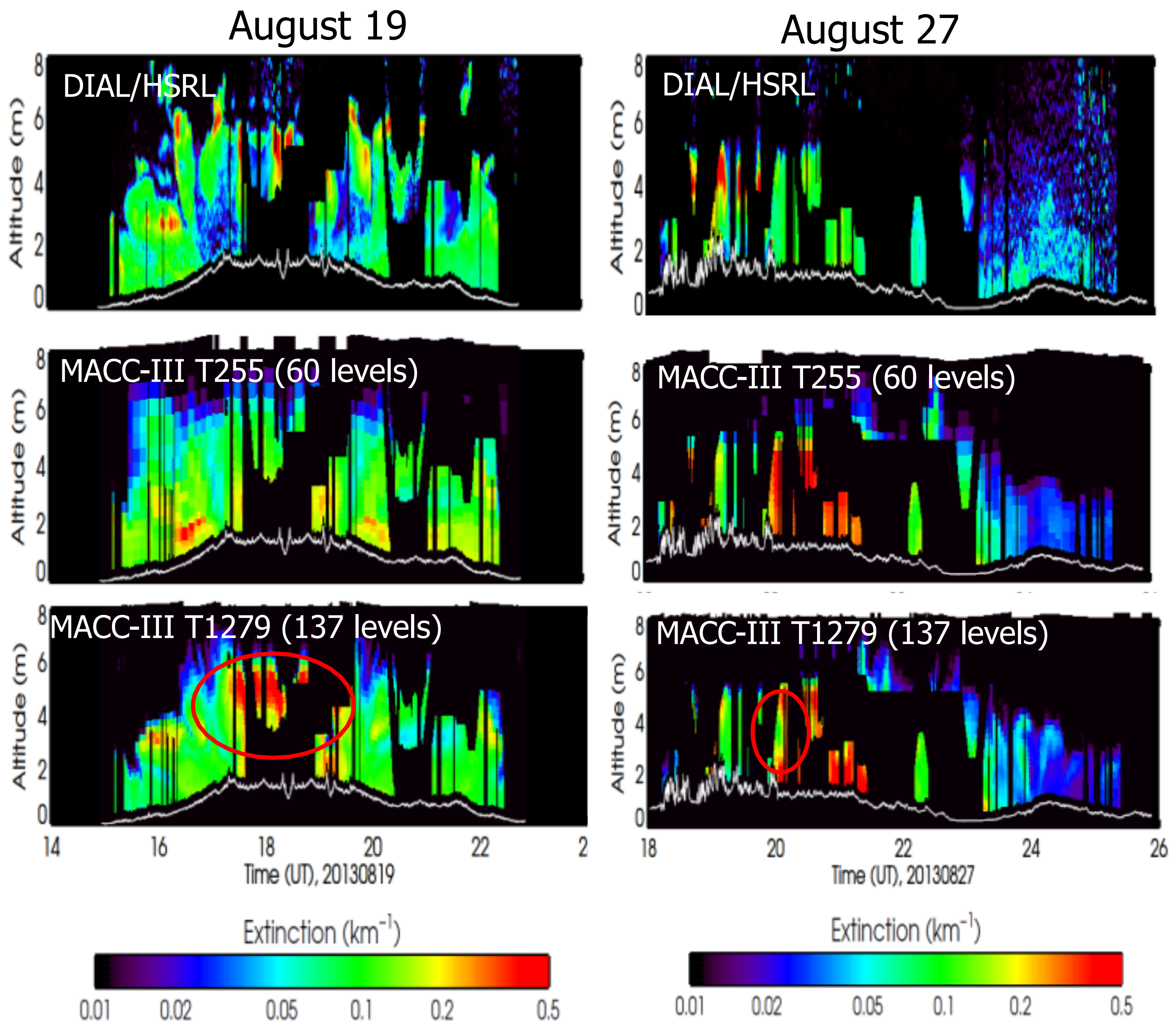
Evaluating the impacts of smoke injection heights computed from plume rise model



- 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

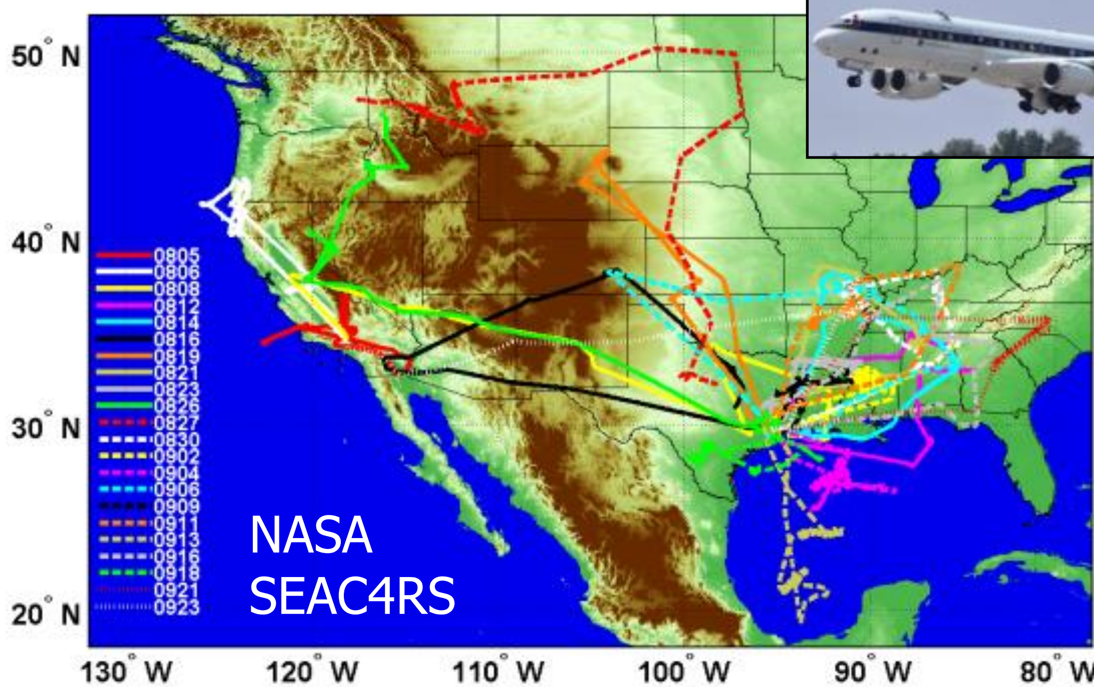
Rémy et al., ACPD, 2016

Evaluating the impact of higher model resolution



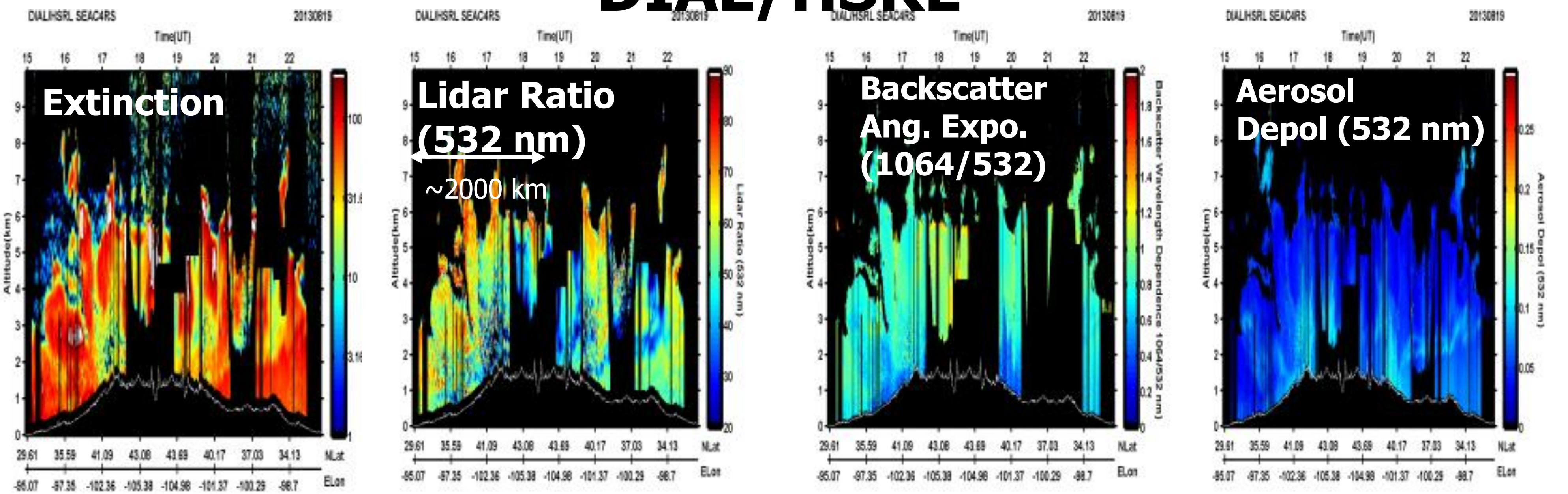
- Model resolution increased from T255 (80 km) with 60 vertical levels to T1279 (16 km) with 137 vertical levels
- Higher resolution represents smoke altitude better than assimilating MODIS AOT or using plume rise model

DIAL/HSRL Comparisons with GEOS-5 During SEAC4RS

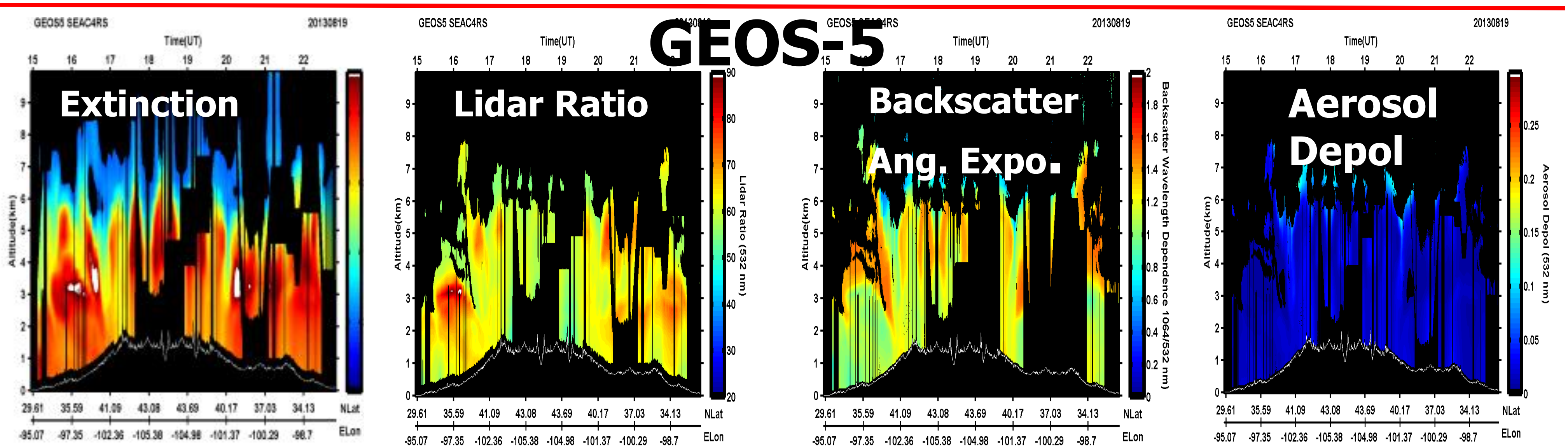


SEAC4RS Aug. 19, 2013 DIAL/HSRL Smoke flight over Midwest

DIAL/HSRL

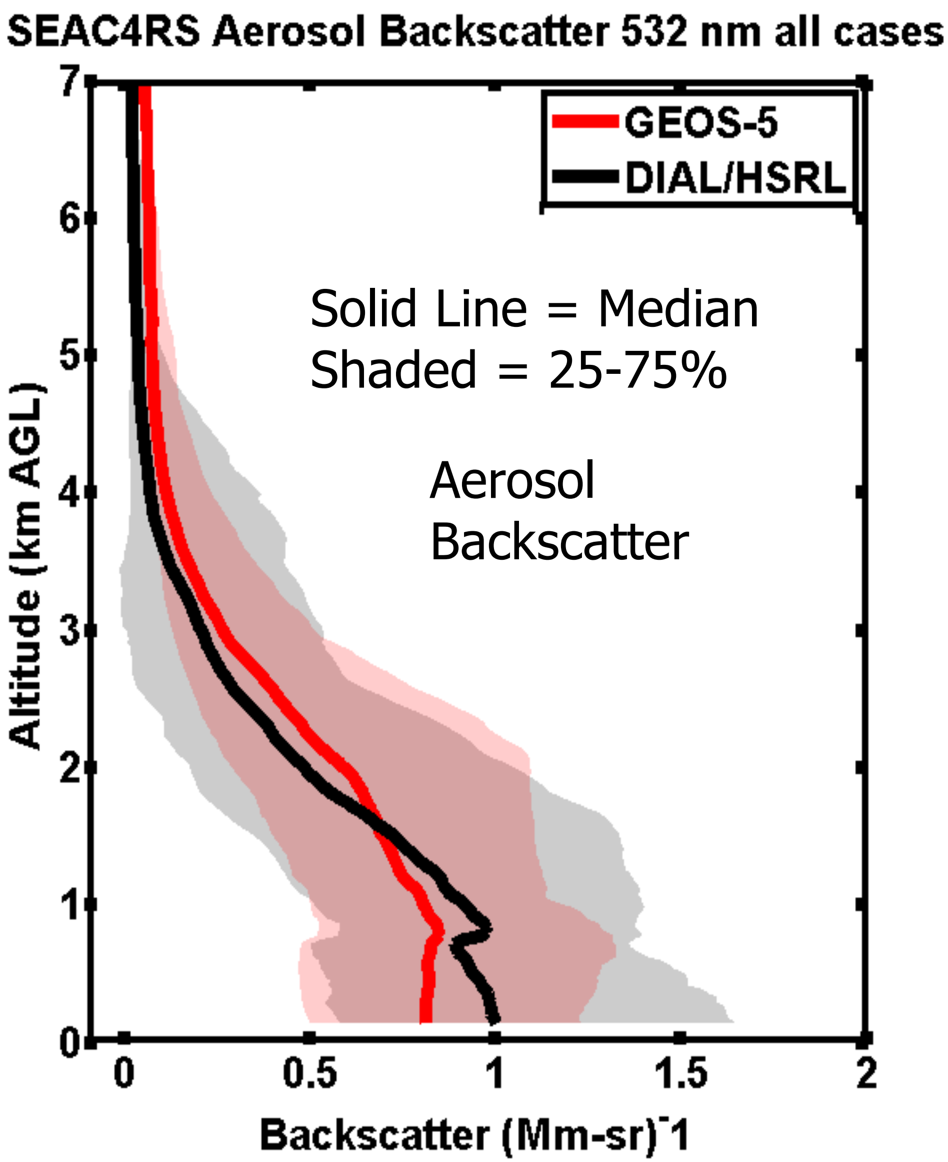


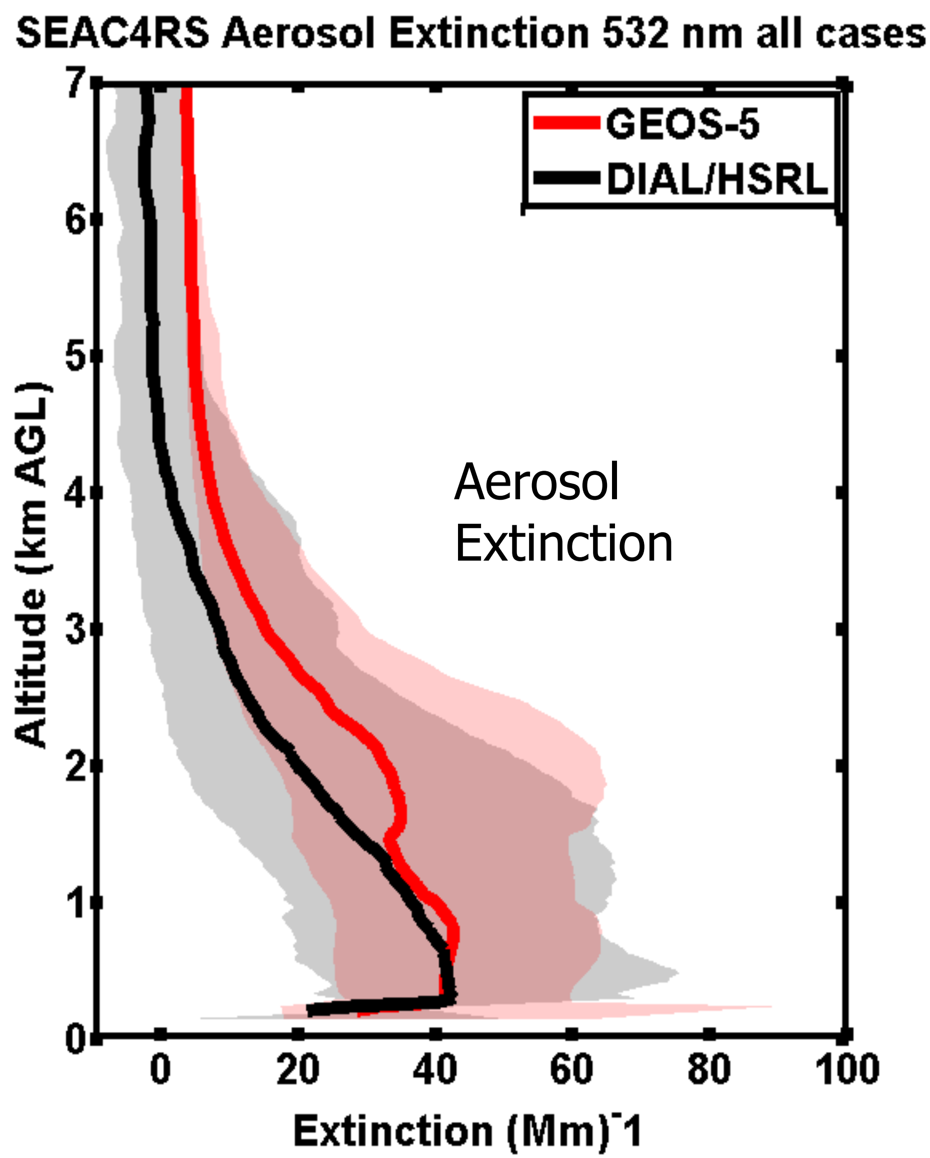
GEOS-5



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

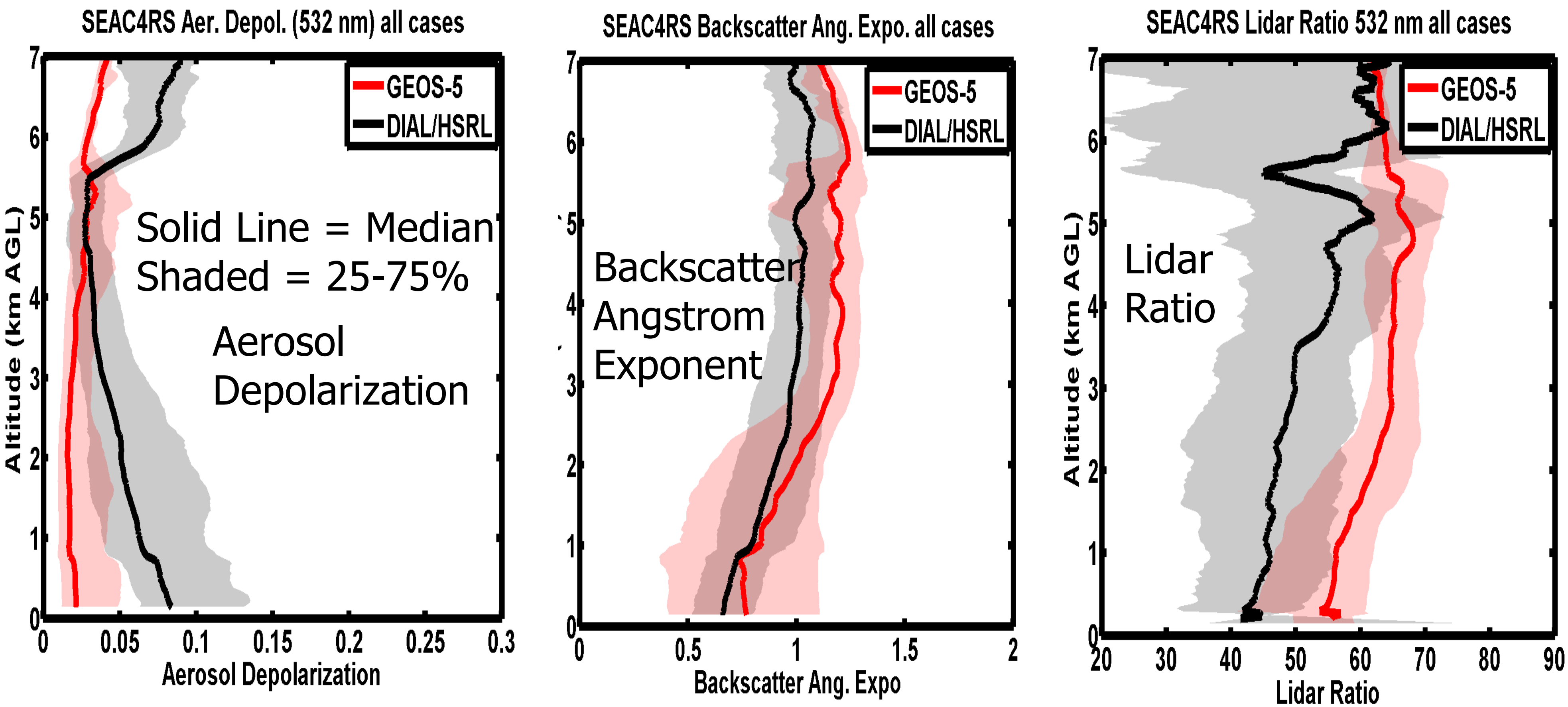
GEOS-5 shows slightly higher backscatter and extinction in free troposphere





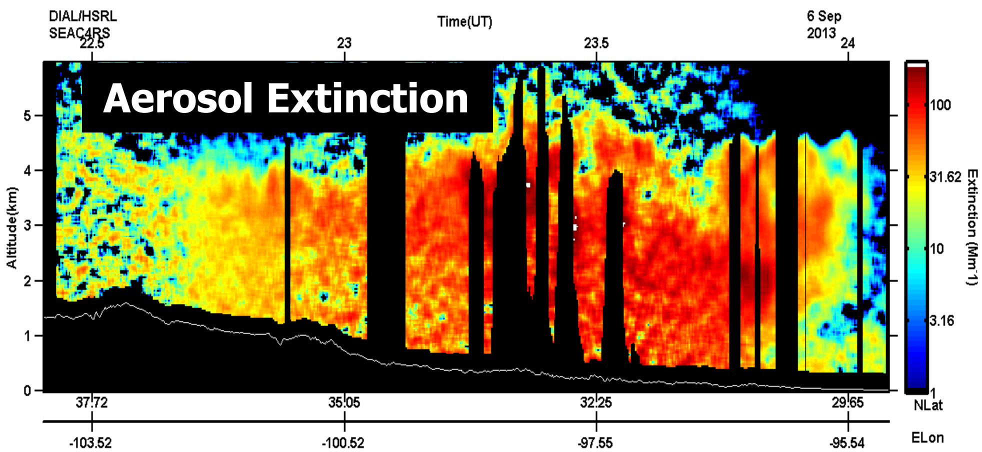
DIAL/HSRL and GEOS-5 Median Intensive Parameter Profiles During SEAC4RS

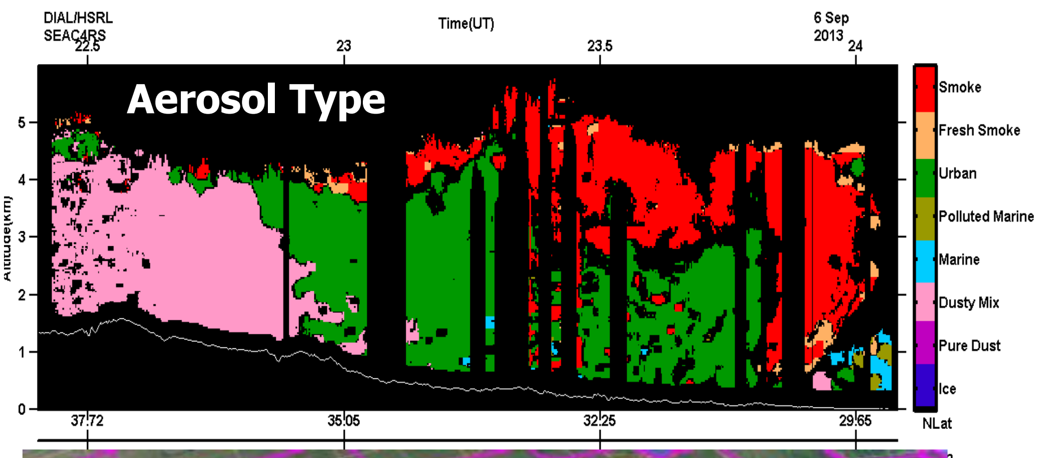
- Both DIAL/HSRL and GEOS-5 intensive parameters vary with altitude suggesting aerosol type varies with altitude
- Backscatter Angstrom exponent increasing with altitude suggests decreasing particle size with height
- GOES-5 lidar ratio higher than DIAL/HSRL
- DIAL/HSRL measured more nonspherical particles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

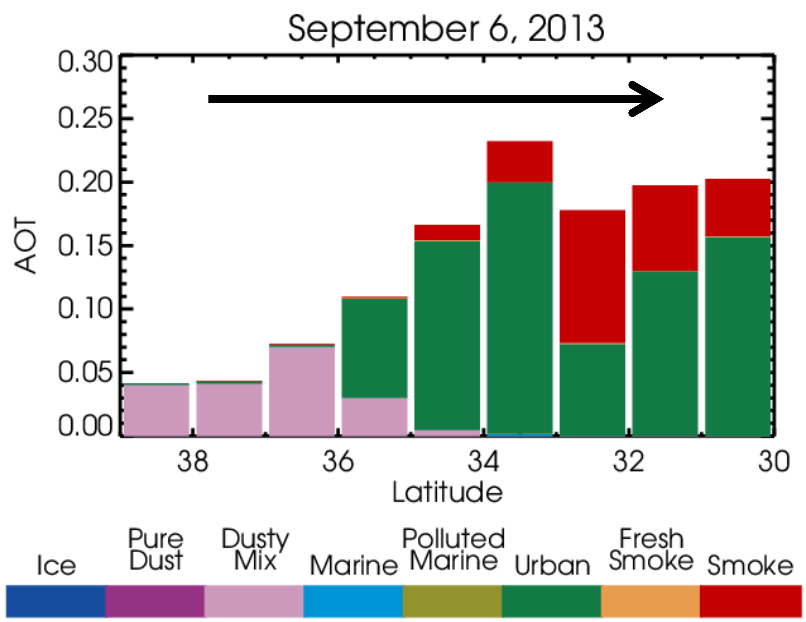


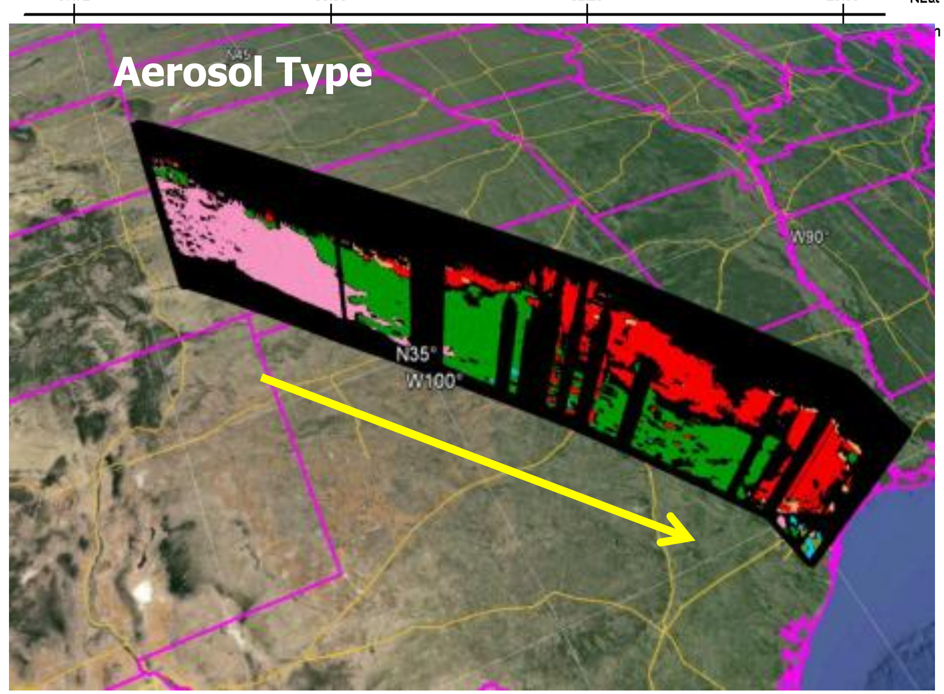
AOT Apportionment to Aerosol Type (Sep. 6) Colorado to Houston

- DIAL/HSRL were used to apportion AOT to aerosol type
- Low AOT over SE Colorado comprised entirely of dusty mix
- Higher AOT over SE Texas comprised of combination of urban and smoke









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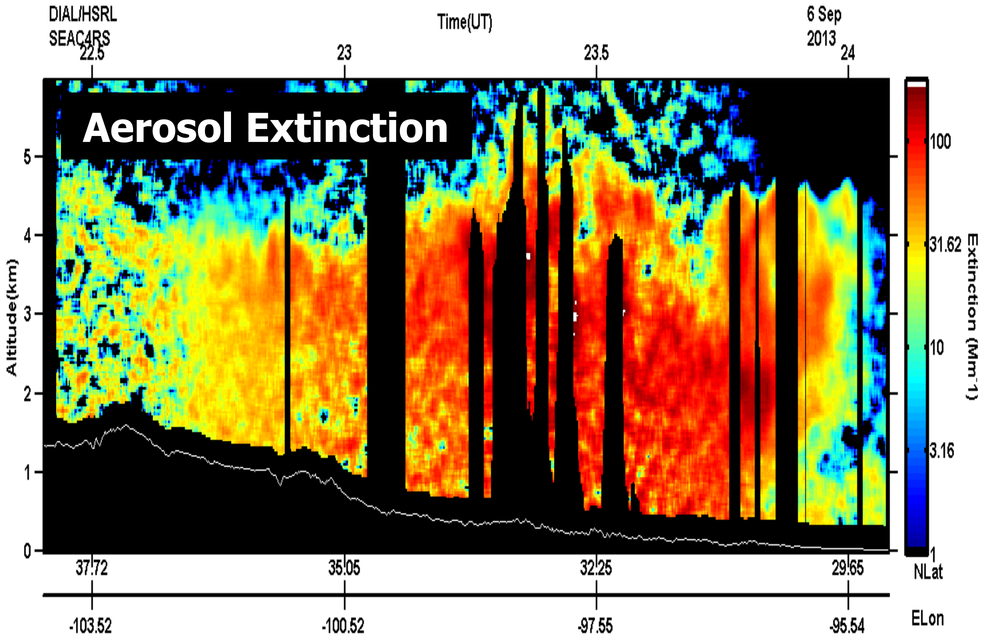
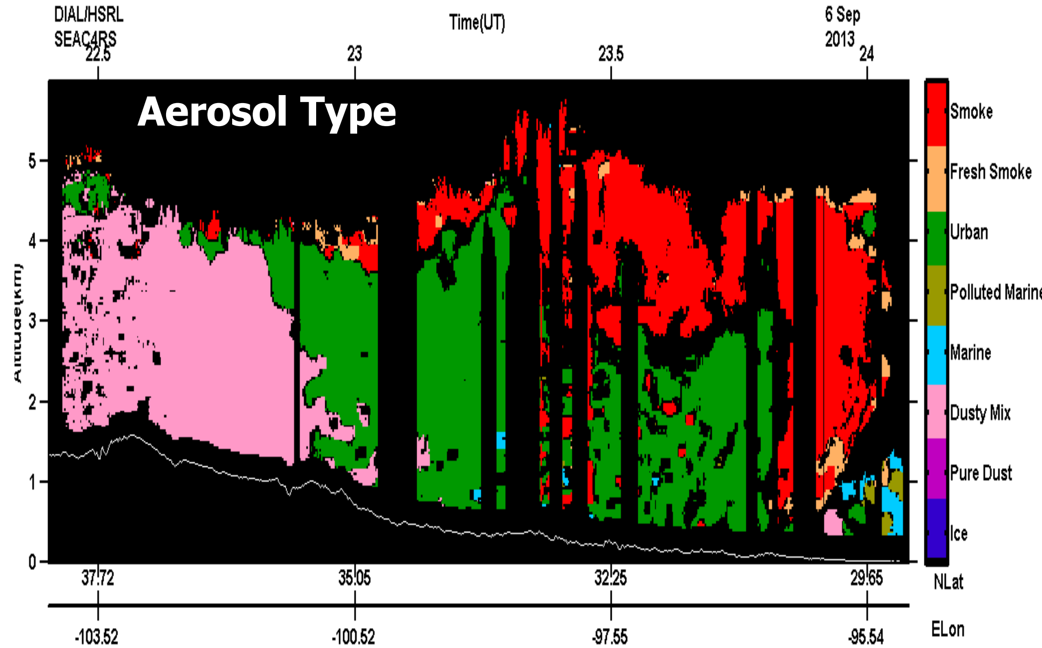
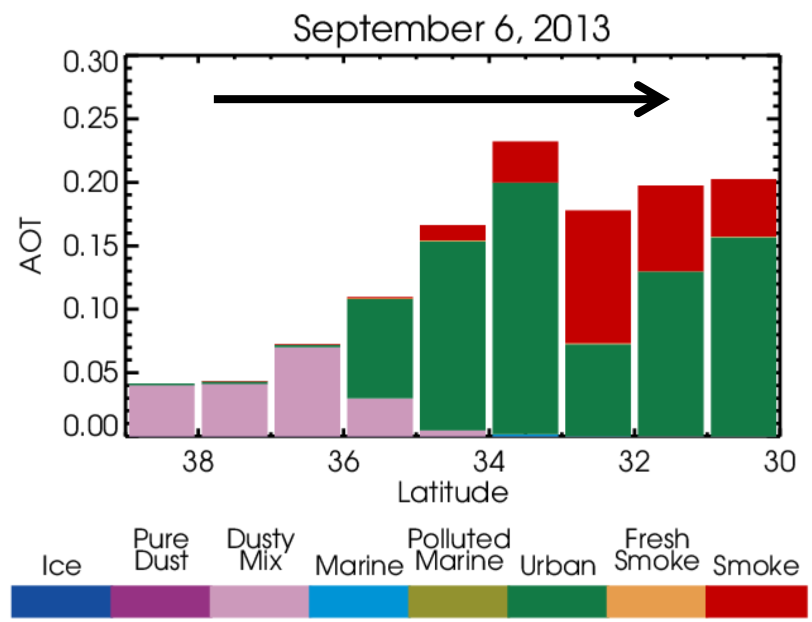


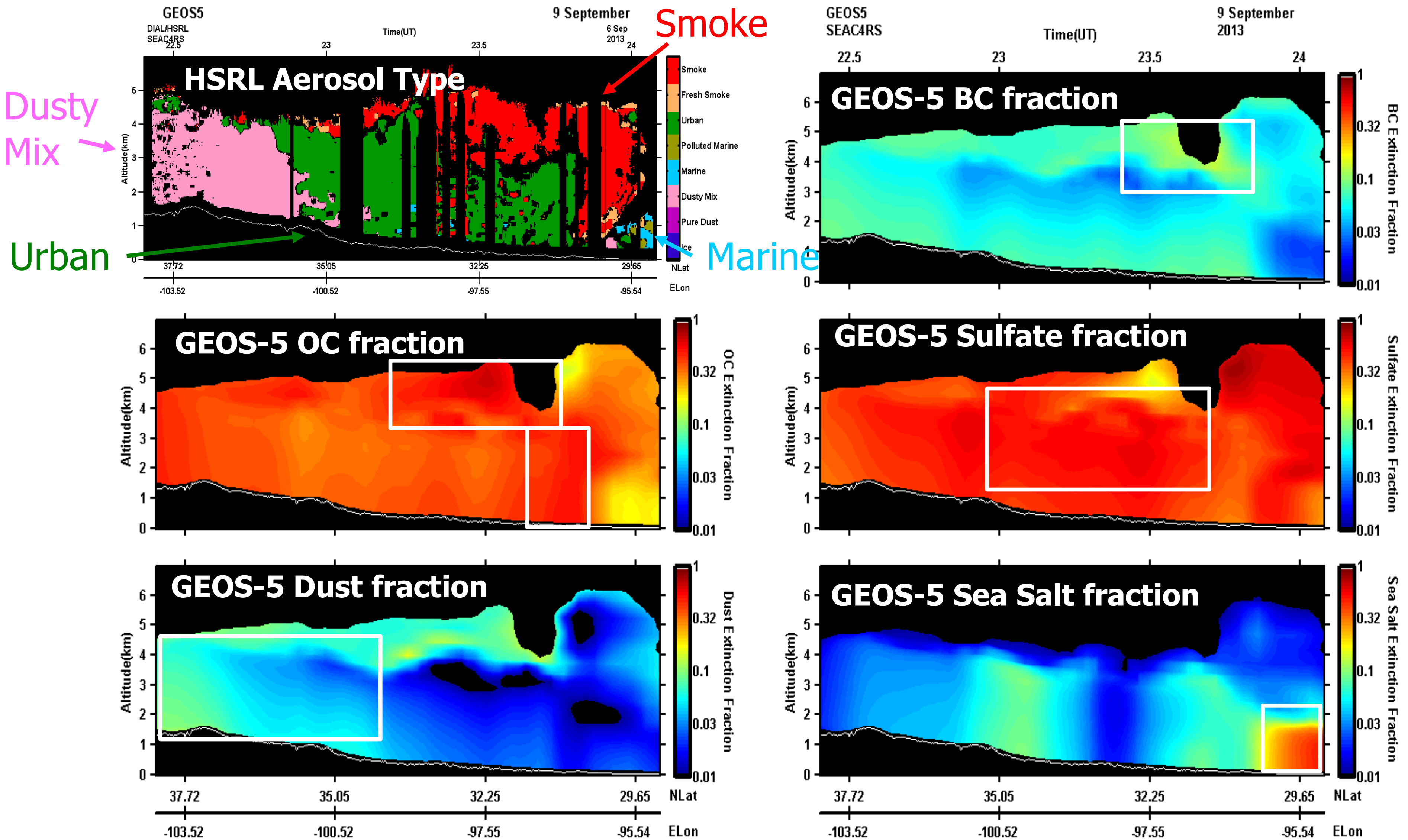




- DIAL/HSRL were used to apportion AOT to aerosol type
- Low AOT over SE Colorado comprised entirely of dusty mix
- Higher AOT over SE Texas comprised of combination of urban and smoke

HSRL aerosol types relate to GEOS-5 aerosol components

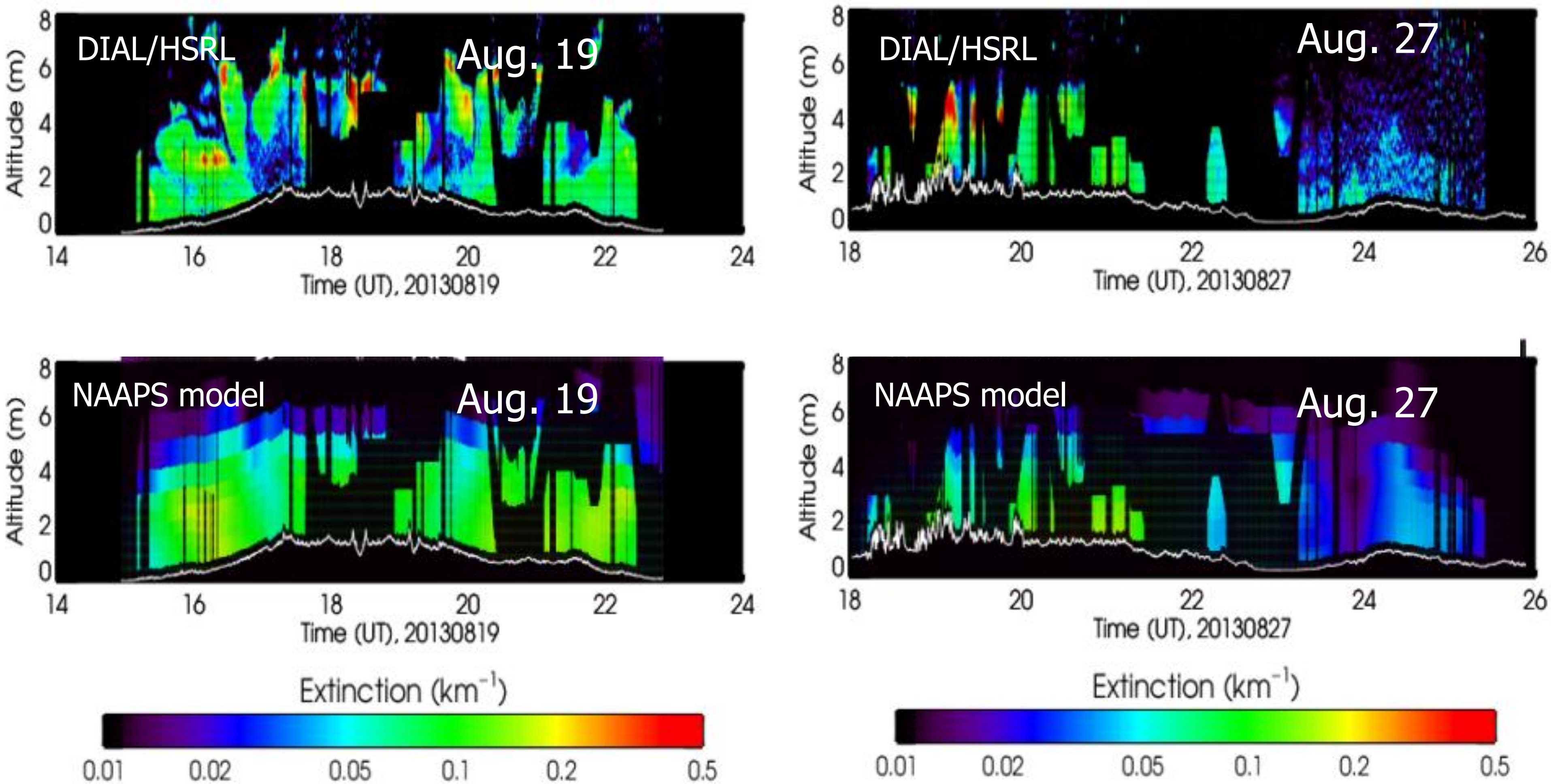
- DIAL/HSRL were used to apportion AOT to aerosol type
- Low AOT over SE Colorado comprised entirely of dusty mix
- Higher AOT over SE Texas comprised of combination of urban and smoke



Preliminary DIAL/HSRL Comparisons with Navy NAAPS Model During SEAC4RS

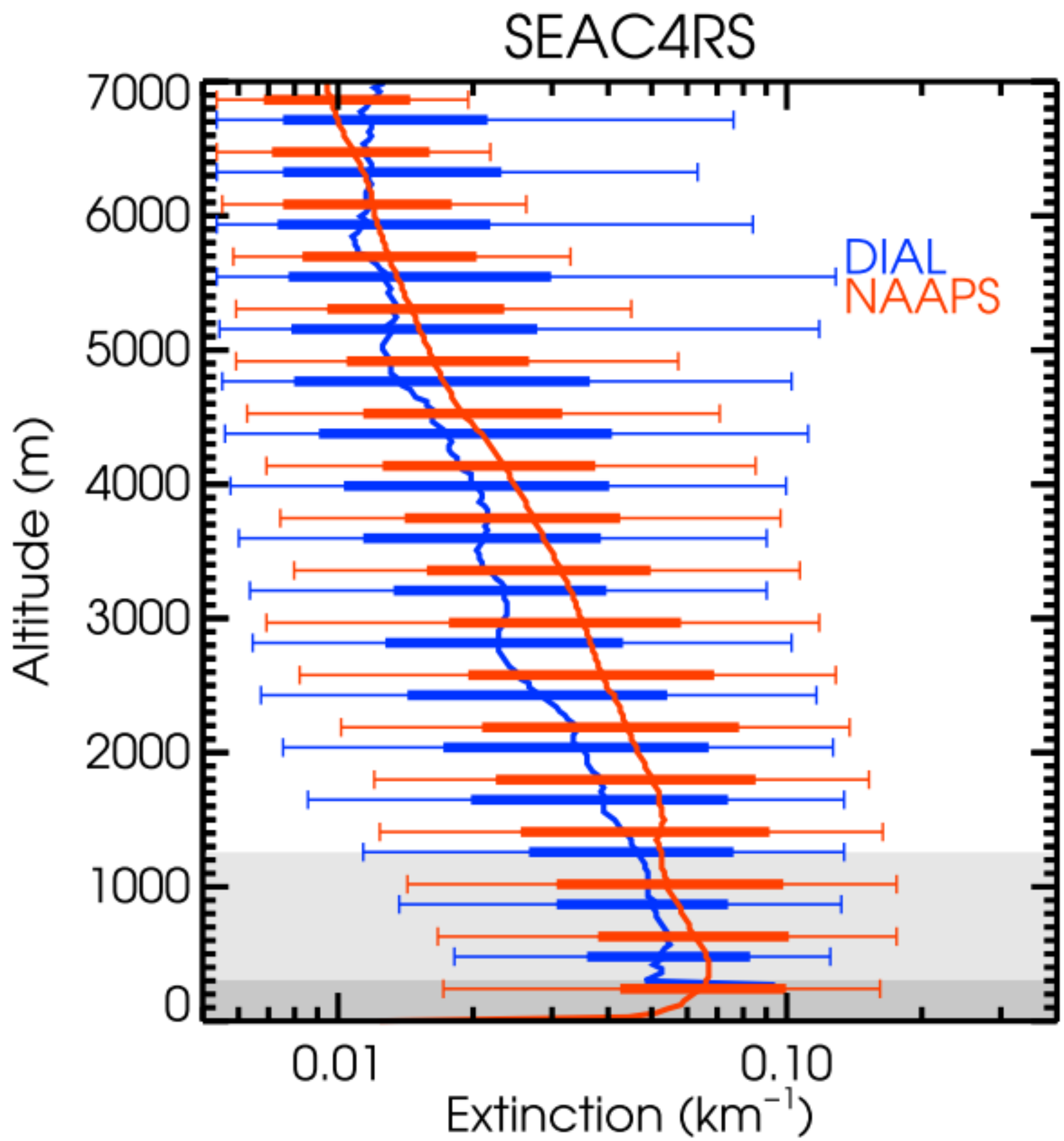
Comparison of NAAPS and DIAL/HSRL aerosol extinction profiles during SEAC4RS

- Aug. 19 case had extensive smoke layers from CA, OR, ID fires
- Aug. 27 had Rim Fire smoke
- Model (with MODIS assimilation) generally gets profile shape and magnitude – misses some of smoke plume peaks



Comparison of NAAPS and DIAL/HSRL aerosol extinction profiles during SEAC4RS

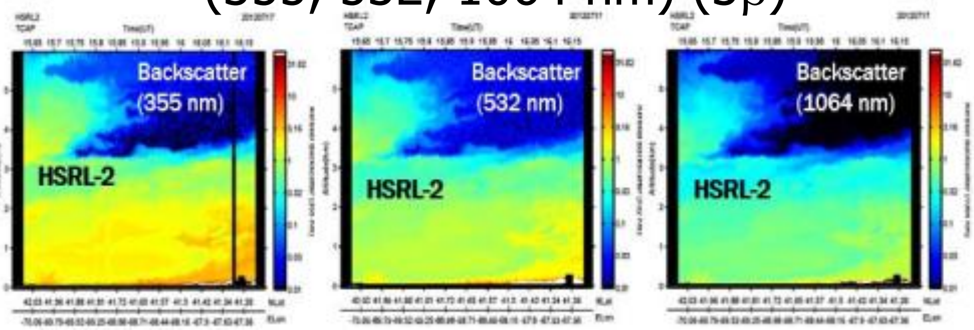
- Median NAAPS profile shape in good agreement with DIAL/HSRL



HSRL-2 Multiwavelength Aerosol Retrievals

Example of Airborne HSRL-2 "3β+2α" Retrievals

Aerosol Backscatter
(355, 532, 1064 nm) (3β)



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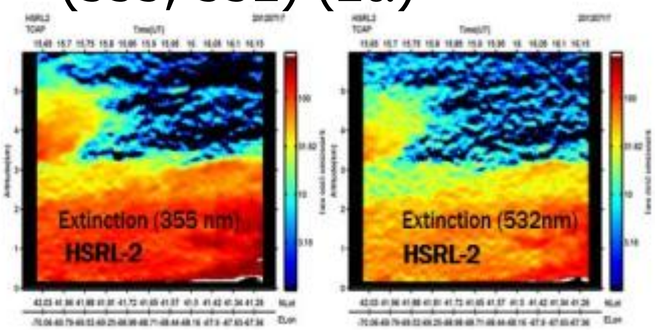
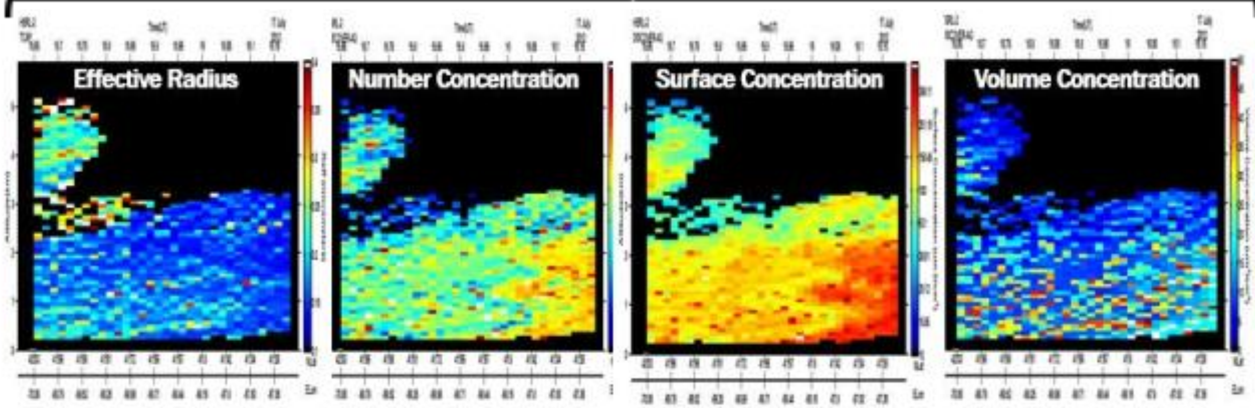
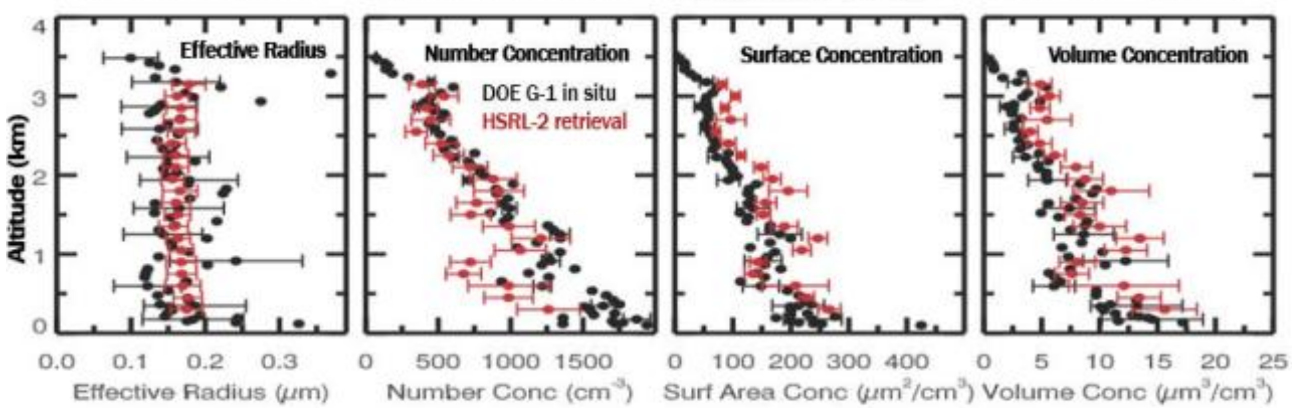
Aerosol Extinction
(355, 532) (2α)



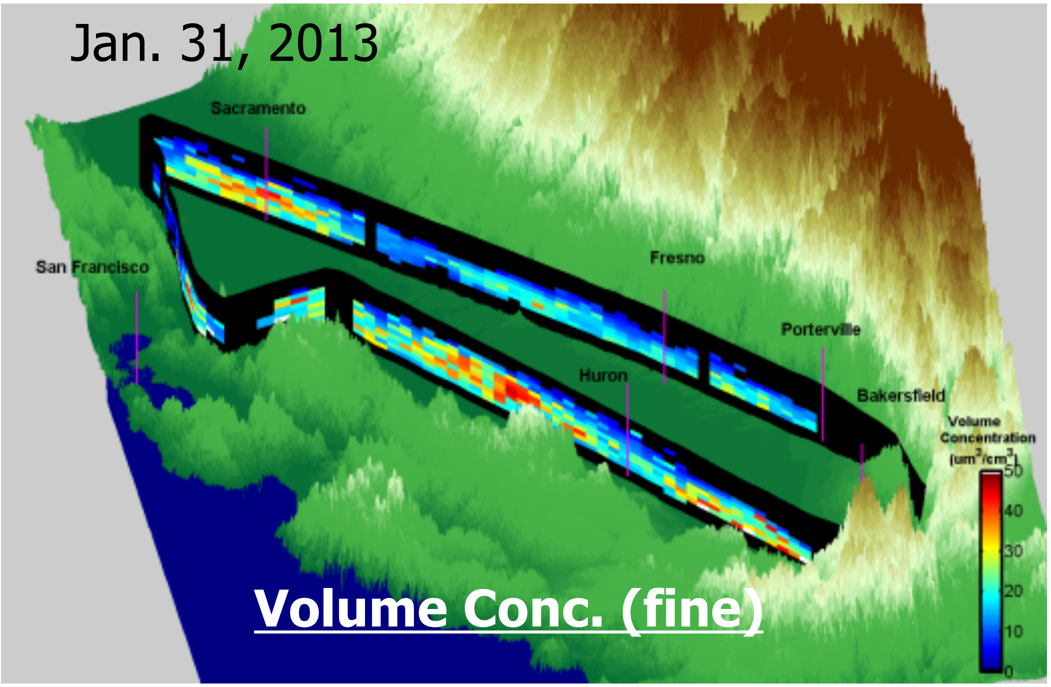




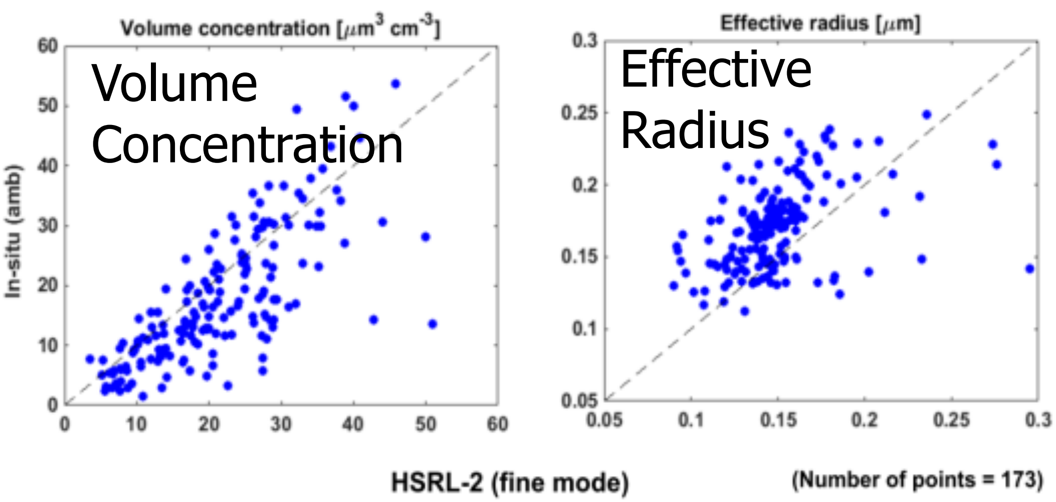
- Multiwavelength lidar retrieval algorithms (e.g. Müller et al., 1998, 1999, 2001; Veselovskii et al., 2002) used to retrieve effective radius and concentration
- Optimal estimation routines under development to combine lidar and polarimeter data to also retrieve refractive index and absorption

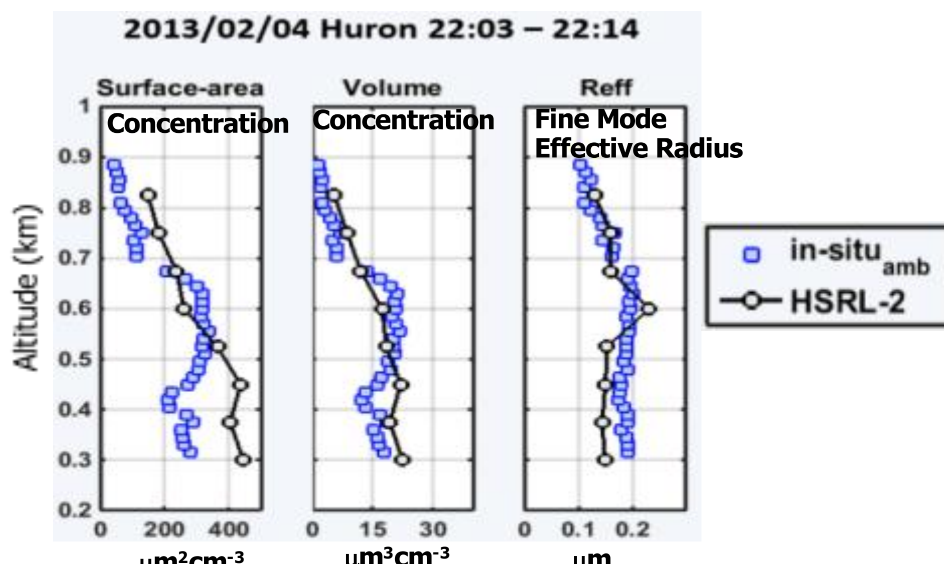
Müller et al., 2014, AMT

HSRL-2 Multiwavelength Aerosol Retrievals (Jan. 31, 2013)



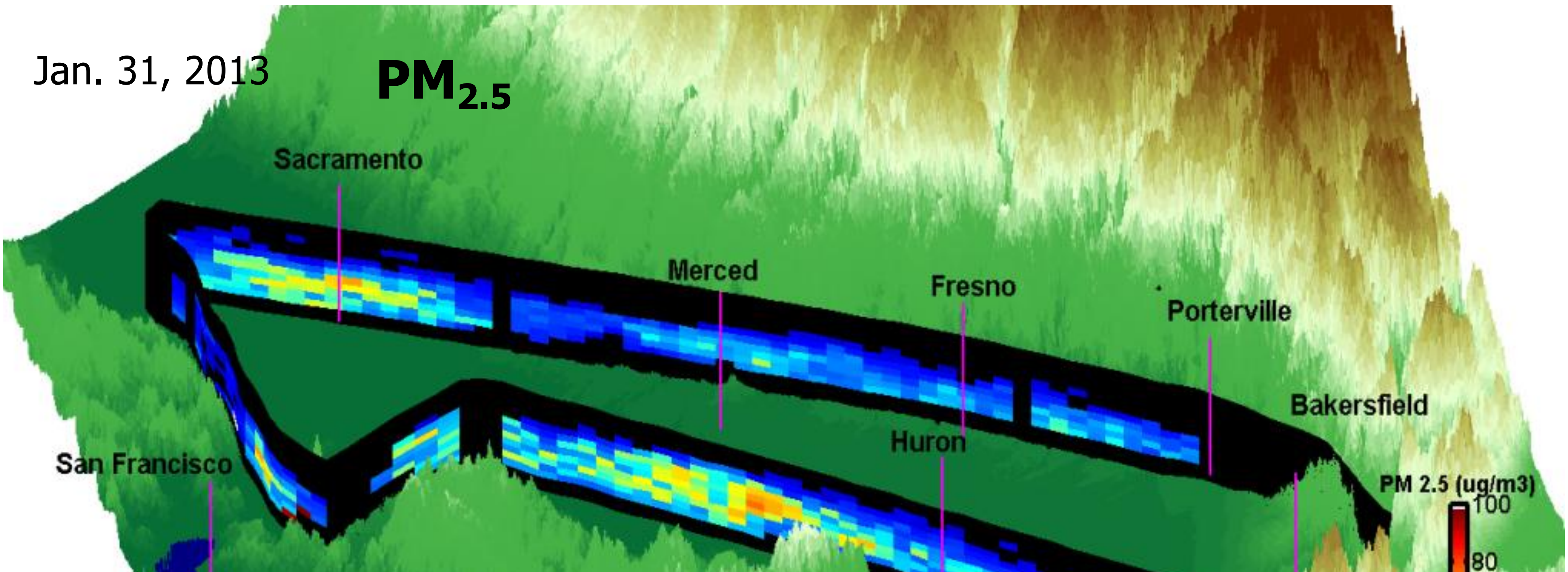
- HSRL-2 multiwavelength measurements of aerosol backscatter and extinction were used to retrieve fine mode aerosol volume concentration and effective radius (e.g. Müller et al., 2014)
- Sawamura et al. (ACPD, 2016) shows the retrievals compare reasonably well with P-3 airborne in situ data

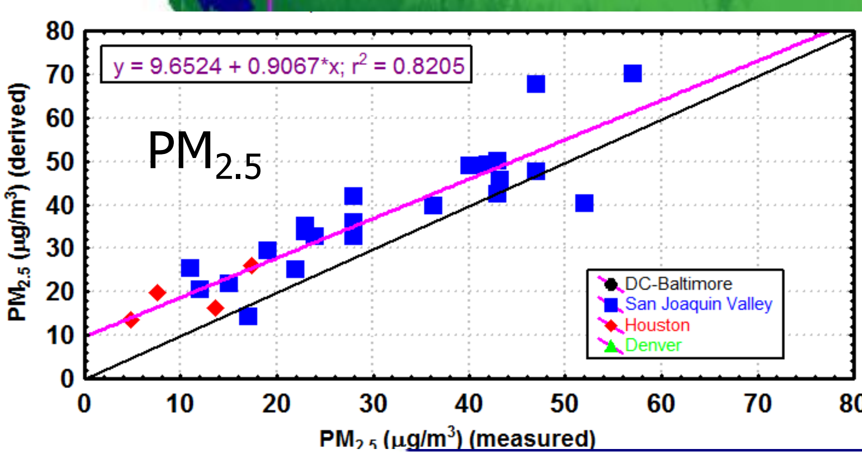




HSRL-2 Retrievals of $PM_{2.5}$ Over Central California (Jan. 31, 2013)

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





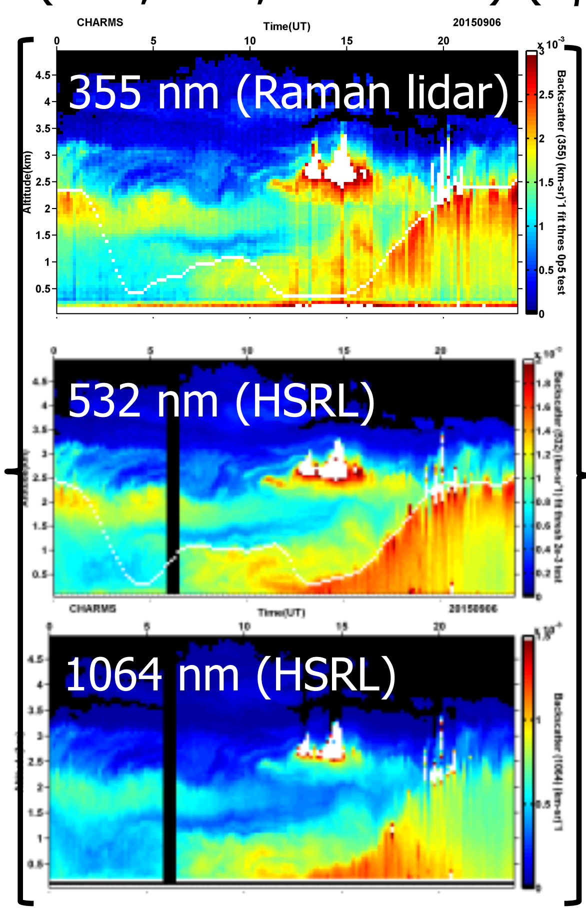
Near-surface derived $PM_{2.5}$ compares well with hourly measured surface values

Ground-Based Multiwavelength "3β+2α" Aerosol Retrievals

ARM Atmospheric Radiation Measurement

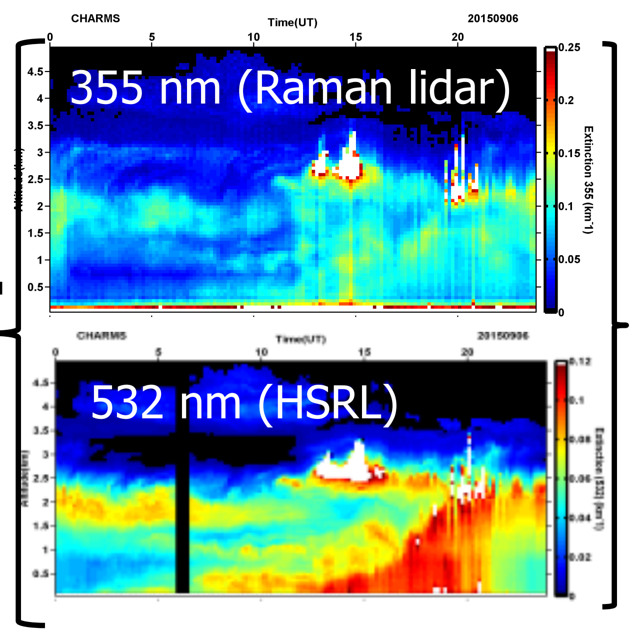
DOE ARM acquired demonstration "3+2" dataset over ARM SGP site in northern Oklahoma during July-September 2015 using DOE SGP Raman lidar and UW HSRL to test feasibility of remotely retrieving aerosol microphysical parameters 24/7

Aerosol Backscatter (355, 532, 1064 nm) (3β)



+

Aerosol Extinction (355, 532) (2α)



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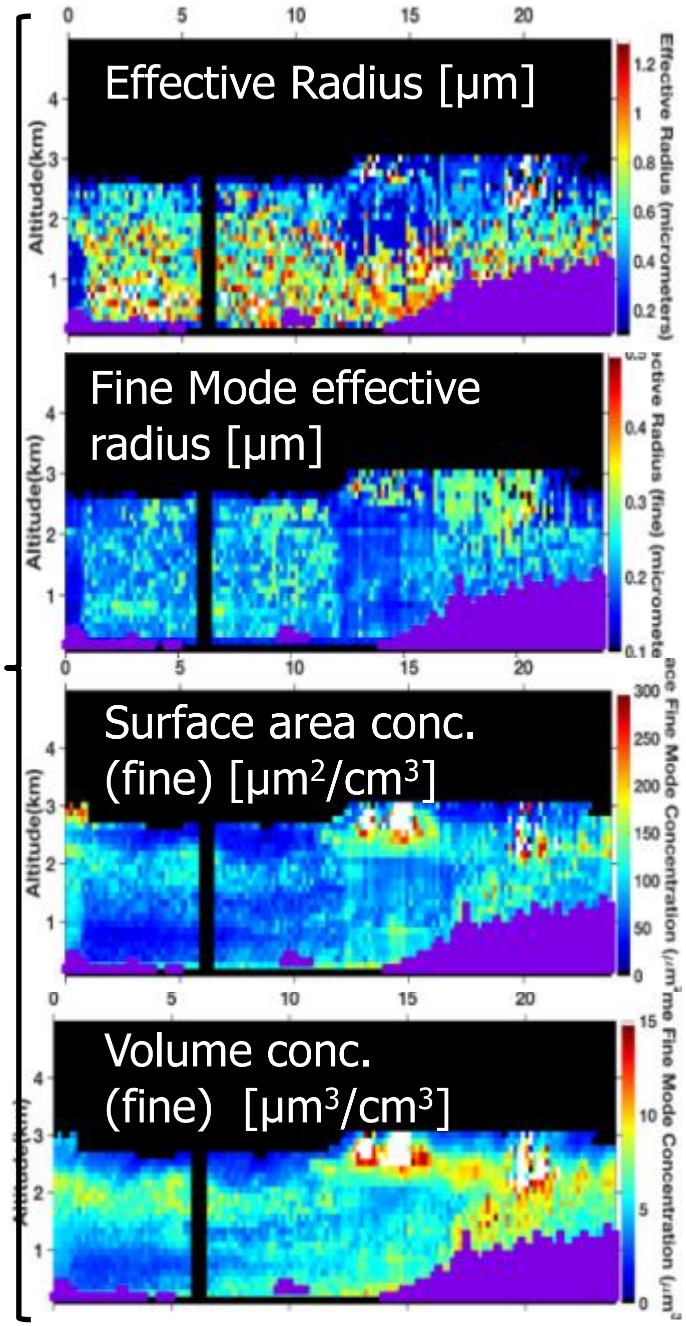
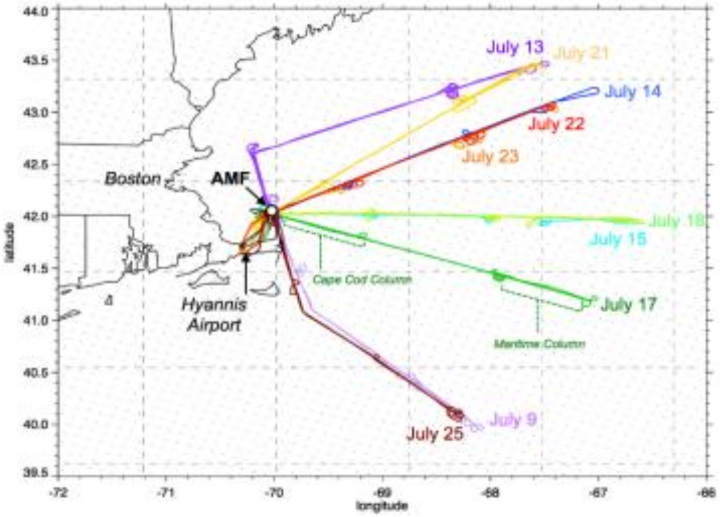


Combined HSRL And Raman lidar Measurement Study (CHARMS)

Summary

- NASA LaRC Airborne HSRLs provide calibrated data products for evaluating models:
  - Aerosol extinction, backscatter, depolarization and AOT profiles
  - Mixed Layer heights
  - Qualitative aerosol classification
  - Retrievals of effective radius, concentration, $PM_{2.5}$
- Much of AOT is often above the daytime mixed layer
- Median ECMWF/MACC and GEOS-5 model extinction profiles in agreement with median DIAL/HSRL profile
- Increased model resolution sometimes improves agreement with DIAL/HSRL
- 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
- HSRL measurements of aerosol intensive parameters may help in evaluating model representations of aerosol speciation
- We plan to continue such model evaluations using HSRL data from recent (ex. KORUS-AQ) and future (ex. NAAMES, ORACLES) field missions

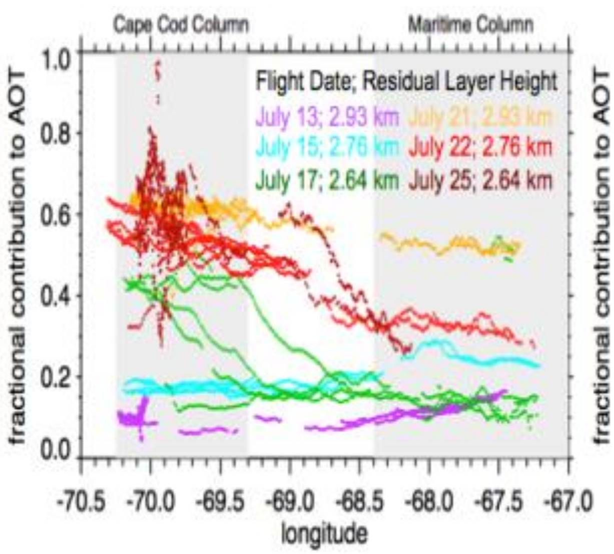
HSRL measurements used to assess model representations of AOT in free troposphere



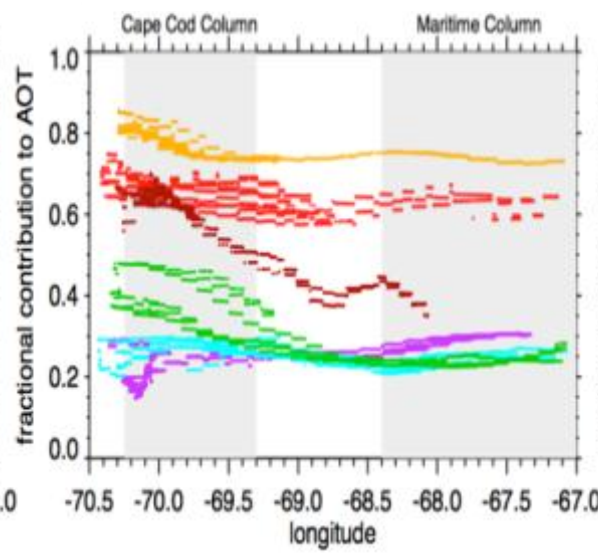
- WRF-Chem (v3.7) and CAM5 model representations of aerosols in the free troposphere were examined during DOE TCAP mission (2012)
- Higher resolution WRF-Chem model produced more aerosols in free troposphere in better agreement with HSRL-2 than coarser resolution CAM5 model

Contribution to AOT by aerosols in free troposphere

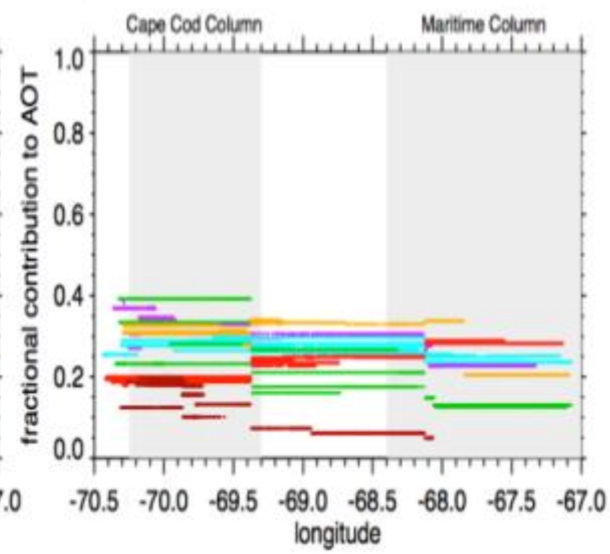
HSRL-2



WRF-Chem



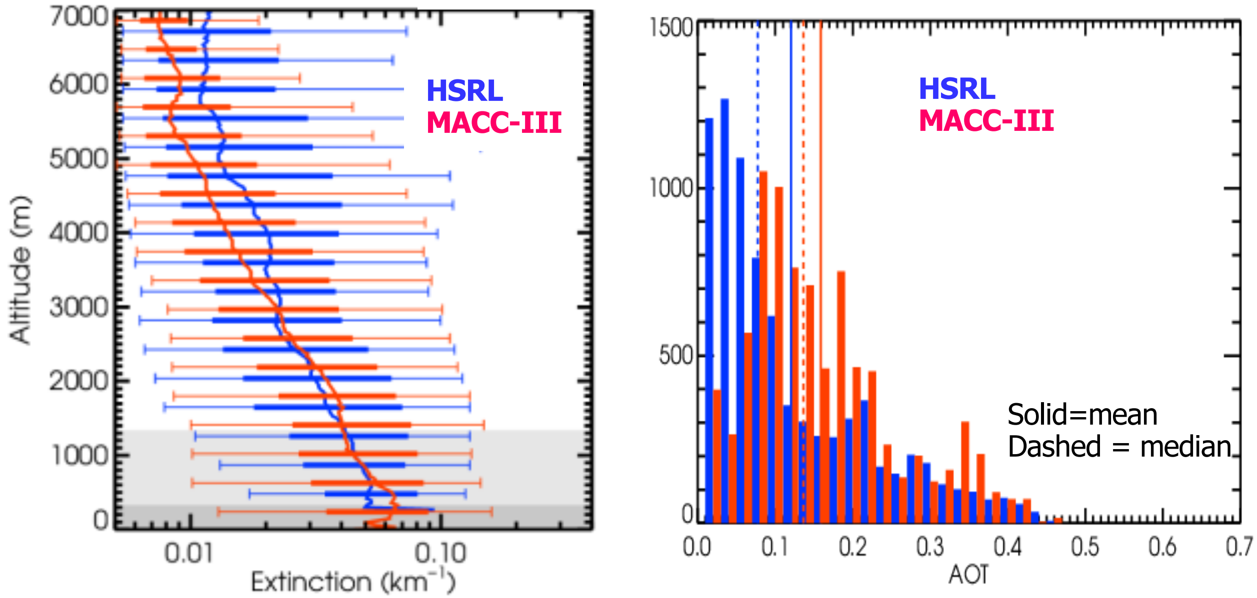
CAM5



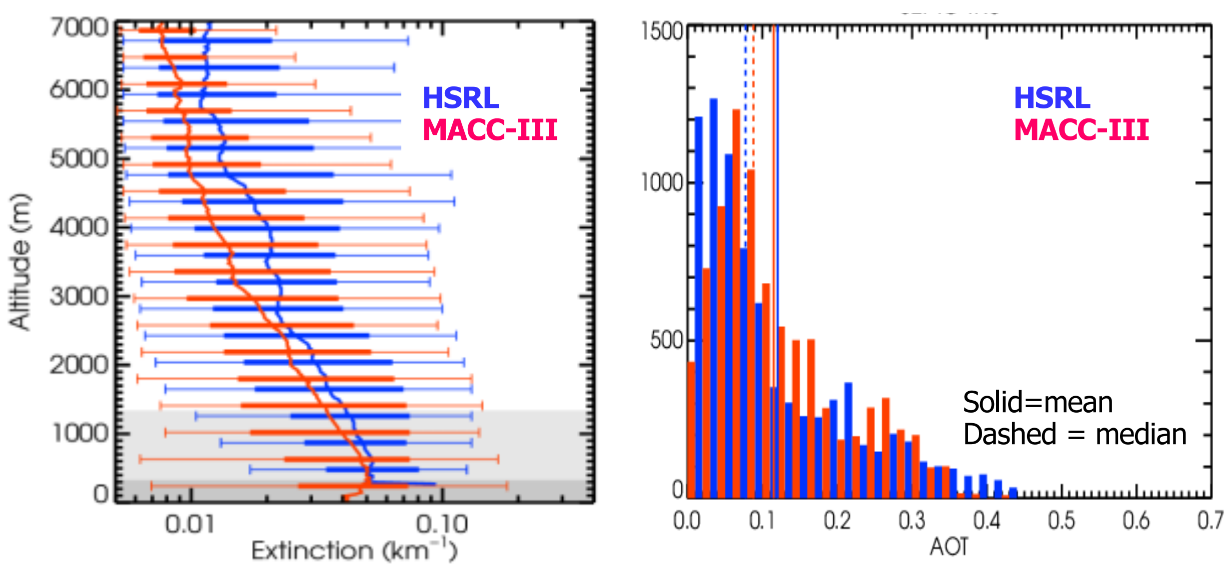
(Fast et al., submitted to JGR, 2016)

Comparison of Median Profiles with and without CALIOP assimilation

MODIS assimilation only



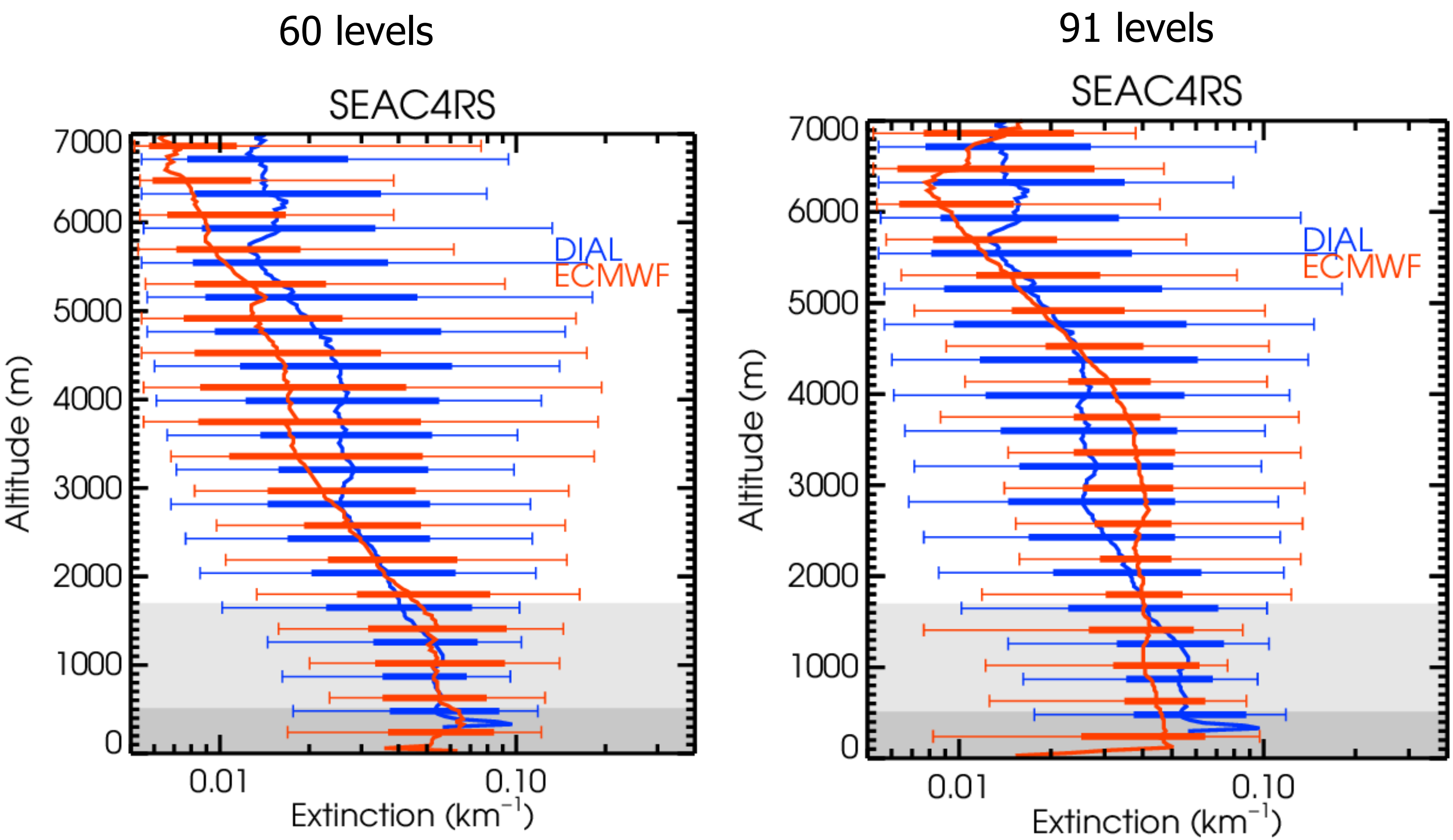
MODIS and CALIOP assimilation



- Median profiles and histograms for entire mission
- Median profiles in good agreement with MODIS AOT assimilation
- Adding CALIOP:
  - produces relatively minor effects on median profiles
  - tends to lower the AOT with respect to runs that assimilate only MODIS AOT – slightly better agreement with HSRL

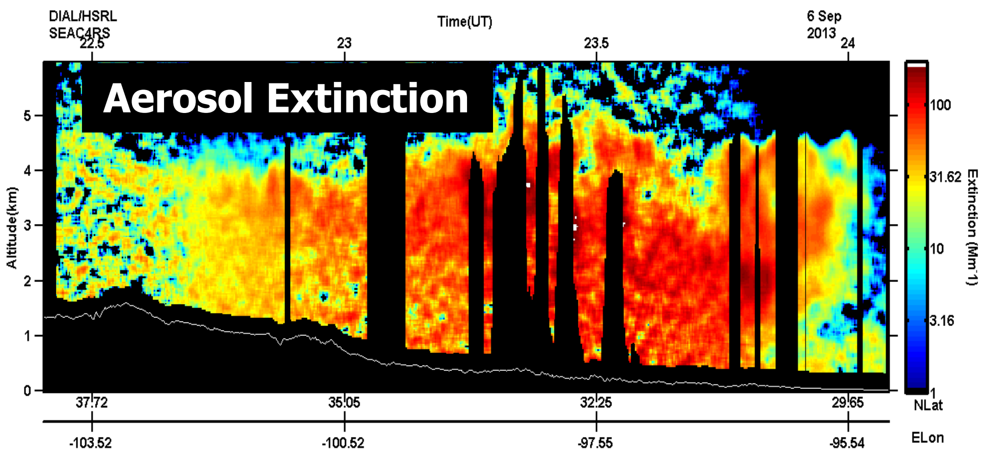
Evaluating the impact of higher model resolution

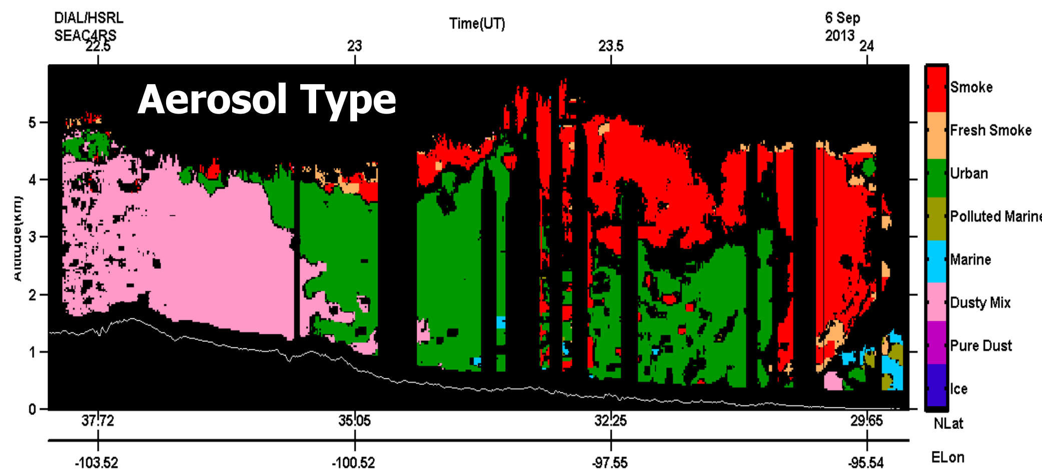
- Increasing number of vertical levels increased extinction in mid troposphere

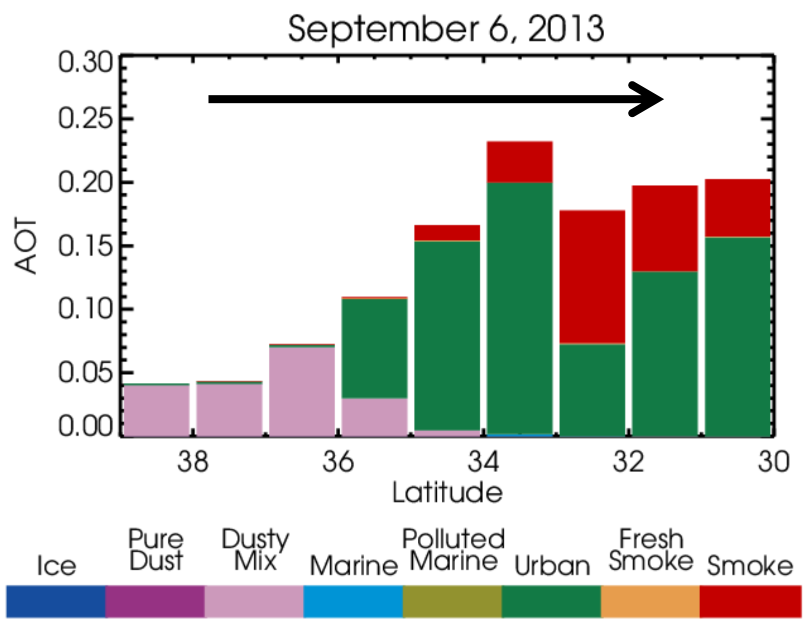


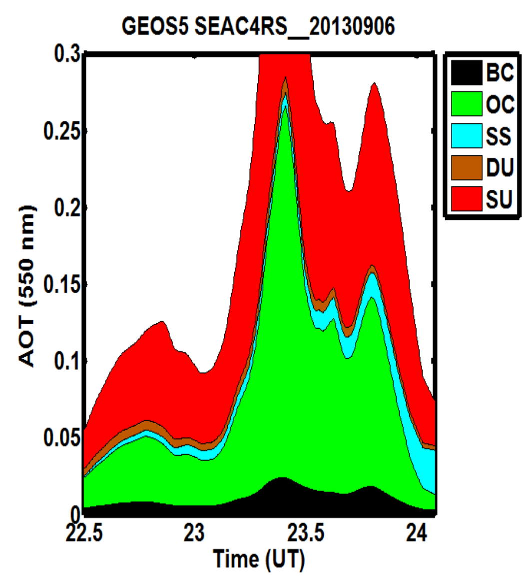
AOT Apportionment to Aerosol Type (Sep. 6) Colorado to Houston

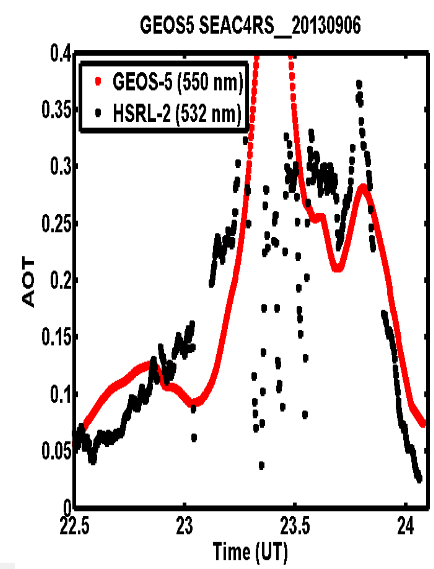
- DIAL/HSRL were used to apportion AOT to aerosol type
- Low AOT over SE Colorado comprised entirely of dusty mix
- Higher AOT over SE Texas comprised of combination of urban and smoke



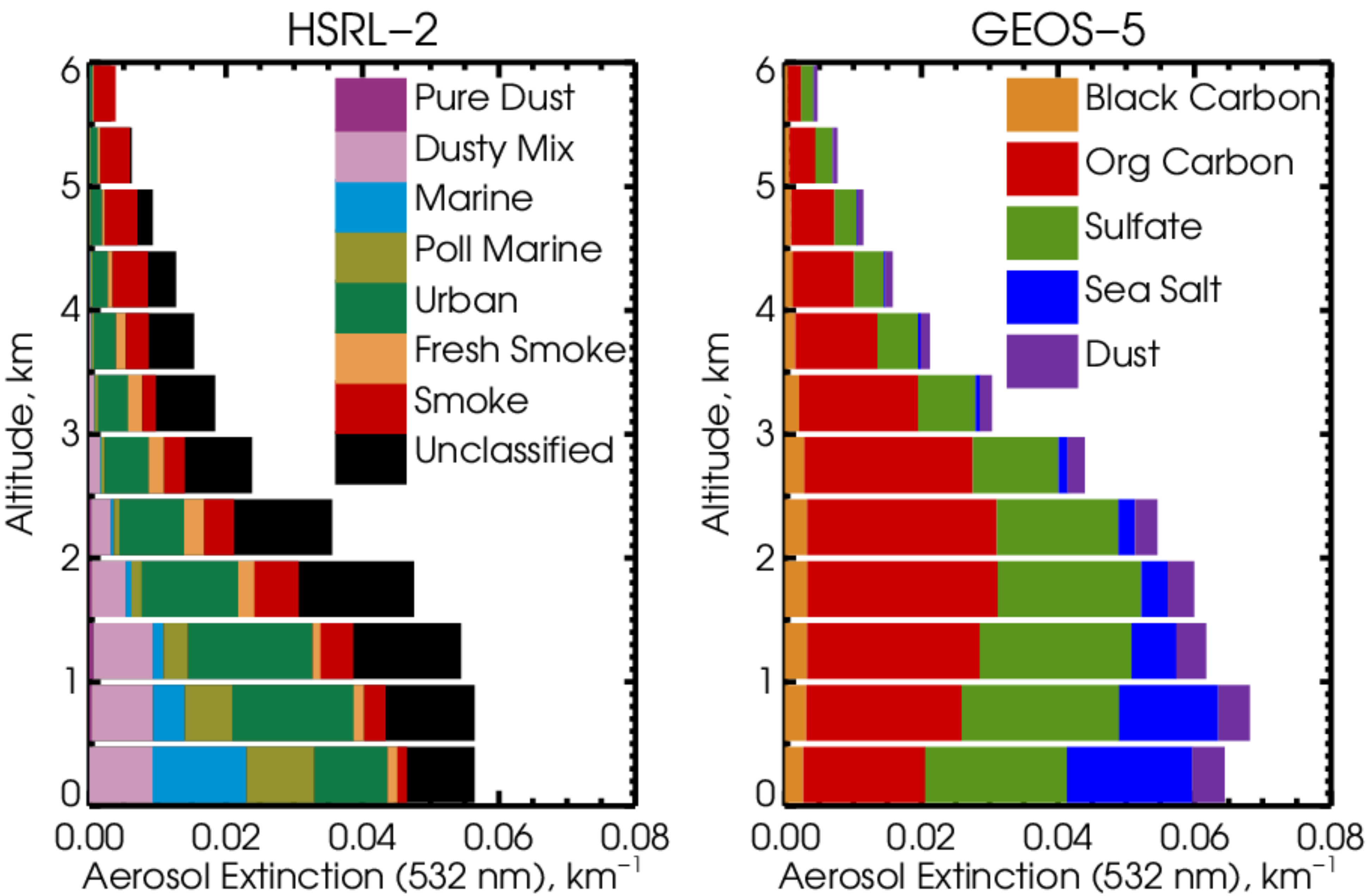




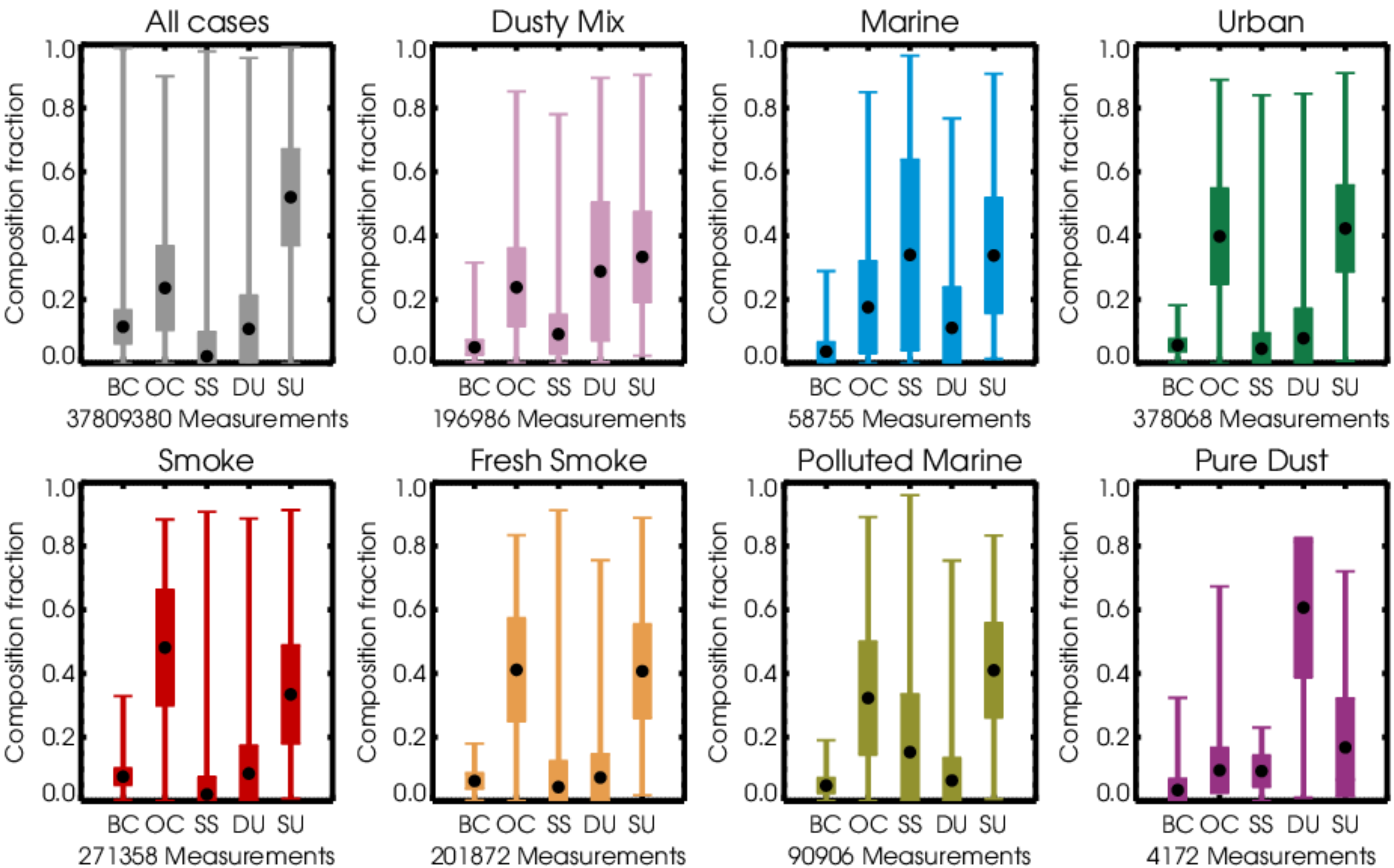




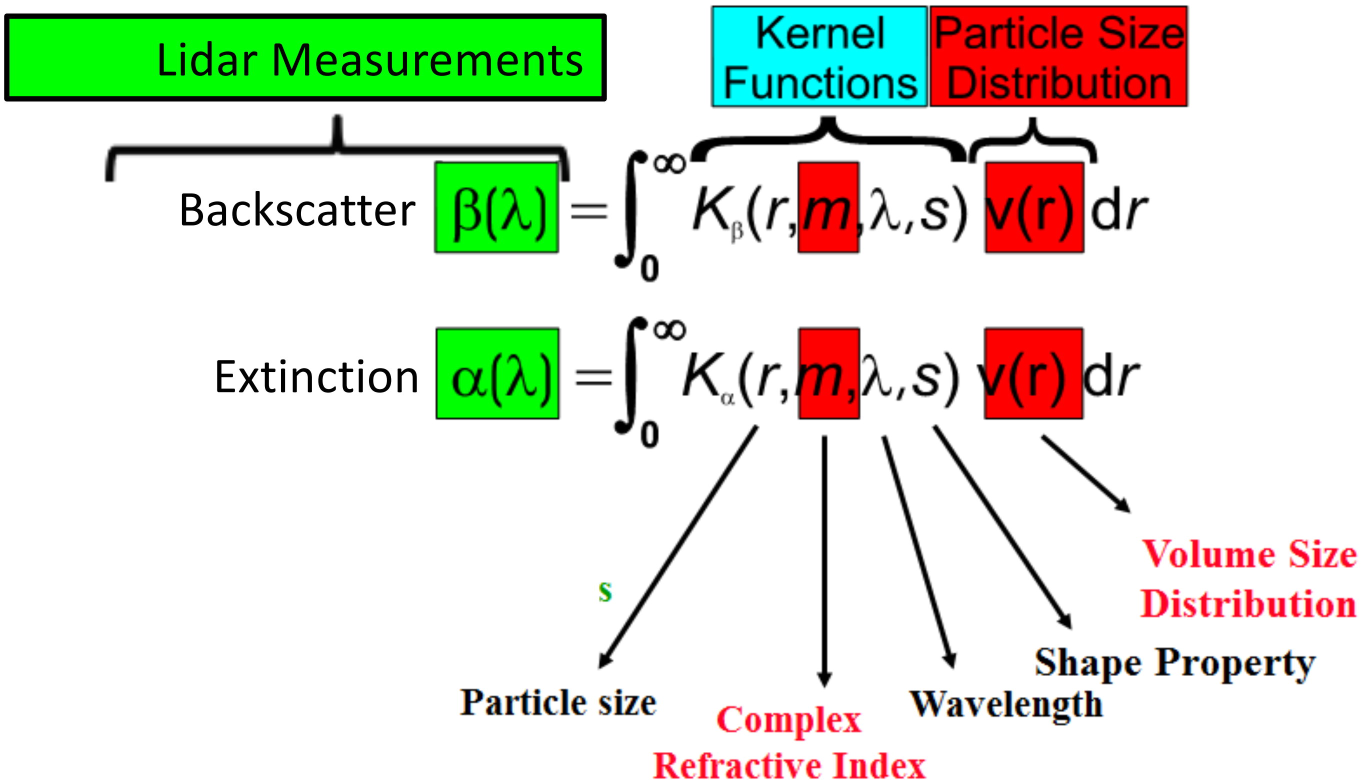
SEAC4RS vertical apportionment of HSRL aerosol type and GEOS-5 aerosol components



GEOS-5 aerosol components are consistent with HSRL aerosol types



- **Input**: aerosol backscatter (3λ) and extinction (2λ): "3β+2α" profiles
- Data inversion with regularization (Müller et al., 1998,1999,2001; Veselovskii et al., 2002)
  - Assumes <u>spherical particles</u>; nonspherical particles retrievals are under investigation



- **Outputs**: effective radius (total, fine, coarse), concentration (number, surface, volume), scattering, absorption coefficients