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
### Field Mission Details

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- 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)
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
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 and aerosol backscatter gradients were about 500-600 m higher than those derived from HSRL-2 and DIAL/HSRL
• 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
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 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
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

Extinction

Lidar Ratio (532 nm)
~2000 km

Backscatter Ang. Expo. (1064/532)

Aerosol Depol (532 nm)

GEOS-5

Extinction

Lidar Ratio

Backscatter Ang. Expo.

Aerosol Depol
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

Solid Line = Median
Shaded = 25-75%

Aerosol Backscatter

Aerosol Extinction
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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HSRL aerosol types relate to GEOS-5 aerosol components

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<th>Aerosol Type</th>
<th>GEOS-5 OC fraction</th>
<th>GEOS-5 BC fraction</th>
<th>GEOS-5 Sulfate fraction</th>
<th>GEOS-5 Dust fraction</th>
<th>GEOS-5 Sea Salt fraction</th>
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**Figure**

- HSRL Aerosol Type
- GEOS-5 BC fraction
- GEOS-5 OC fraction
- GEOS-5 Sulfate fraction
- GEOS-5 Dust fraction
- GEOS-5 Sea Salt fraction
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 “$3\beta+2\alpha$” Retrievals

- Aerosol Backscatter (355, 532, 1064 nm) ($3\beta$)
- Aerosol Extinction (355, 532) ($2\alpha$)

- 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

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)

Effective Radius [μm]

Fine Mode effective radius [μm]

Surface area conc. (fine) [μm²/cm³]

Volume conc. (fine) [μm³/cm³]

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\textsubscript{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

(Fast et al., submitted to JGR, 2016)
Comparison of Median Profiles with and without 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

60 levels

91 levels

![Graph showing extinction in mid troposphere with 60 and 91 levels]
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
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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 ($3\lambda$) and extinction ($2\lambda$): “$3\beta + 2\alpha$” profiles

Data inversion with regularization (Müller et al., 1998, 1999, 2001; Veselovskii et al., 2002)
  – Assumes spherical particles; nonspherical particles retrievals are under investigation

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