

A strategy for reducing uncertainty in the aerosol direct radiative effect through synergistic use of satellite, ground-based in situ, remote sensing, and Citizen Science measurements

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Talk Outline

Objective: Introduce opportunity for ground-based aerosol network sites (NOAA-ESRL, ideally co-located with sunphotometer and a lidar or ceilometer) to better constrain satellite-derived aerosol properties. This would lead to improvements in satellite aerosol retrieval algorithms, estimates of aerosol direct radiative effect, and (hopefully) chemical transport models

- I. Uncertainties in the aerosol direct radiative effect (DRE)
- II. The need for ground-based aerosol networks to reduce DRE uncertainties and evaluate/improve models
- III. How do satellites (i.e. MISR) retrieve 'aerosol type'?
- IV. Constraining MISR aerosol air mass types through PDFs of in situ-measured aerosol properties-Opportunity for NOAA-ESRL Network?
- V. Sample data to illustrate method for evaluating and constraining MISR-retrieved aerosol type
- VI. Conclusions, challenges and future work

I. Uncertainties in the aerosol direct radiative effect

- Despite recent advances in satellite-based remote sensing of aerosols, the aerosol direct and indirect radiative effects still represent major sources of uncertainty in climate models (IPCC 2013).
- Aerosol DRE is most sensitive to spectral aerosol optical depth (AOD), with comparable sensitivity to particle properties such as single-scattering albedo (ω_0), once mid-visible AOD reaches ~ 0.15 . (Sherman and McComiskey, ACP 2018)
- Angular scattering properties (often asymmetry parameter, g) and surface albedo also contribute a smaller amount to DRE uncertainties (Sherman and McComiskey, ACP 2018), along with vertical aerosol distribution.

Current uncertainties of aerosol radiative properties retrieved by satellites and ground-based networks

- To estimate DRE to within $\sim 1 \text{ Wm}^{-2}$, both spectral AOD and ω_0 must be known to within ~ 0.02 (Sherman and McComiskey, 2018), which is possible for collocated NOAA-ESRL sites (possessing humidified scattering measurements) and sunphotometers (AERONET or MFRSR).
- In contrast to AOD, all space-based aerosol remote-sensing instruments provide no better than qualitative constraints on particle properties such as ω_0 , g , along with size distributions and refractive indices used by Mie Theory to calculate ω_0 and g (Kahn 2011; Kahn and Gaitley, 2015).
- Kahn and Gaitley (2015) reported that the categorical MISR retrieval “aerosol type”, representing the aggregate of particle size, shape, and ω_0 constraints, yields a more robust MISR retrieval variable than any of these individual aerosol properties. **However, they recommend that even this be used only qualitatively**

Parameter	Ground-based measurement uncertainty (Source)	Satellite-based measurement uncertainty
AOD (visible)	0.01-0.015(Eck et al., 1999; Hallar, et al., 2015)	0.05± 15 to 20% (Levy, 2010;Kahn 2011)
ω_0 (visible)	0.02-0.03 (Sherman et al., 2015; Titos et al, 2016)	????? (Kahn and Gaitley, 2015)
g (visible)	0.01 (Sherman et al., 2015; Titos et al., 2016)	????? (Kahn and Gaitley, 2015)
R		0.05*R (Vermote and Saleous, 2006)

Top-of-atmosphere (TOA) DRE Uncertainties at APP

- Table from Sherman and McComiskey, ACP, 2018
- Uncertainties (units: Wm^{-2}) calculated using seasonal median aerosol optical properties at APP ('base case values') as inputs to SBDART radiative transfer model, along with aerosol property uncertainties shown on previous slide and DRE sensitivities (Sherman and McComiskey, 2018)
- DRE uncertainties calculated using AOD from MODIS are given in parentheses

	MAR	JUN	SEP	DEC
$\Delta\text{DRE}_{\text{AOD}}$	0.47 (2.3)	0.35 (1.8)	0.34 (1.7)	0.43 (2.1)
$\Delta\text{DRE}_{\omega_0}$	0.27	0.77	0.36	0.079
ΔDRE_g	0.059	0.18	0.12	0.018
ΔDRE_R	0.16	0.34	0.18	0.04
ΔDRE	0.58 (2.3)	1.1 (2.2)	0.74 (2.0)	0.45 (2.1)
DRE (Base case)	-2.4	-5.7	-3.6	-0.91
$\Delta\text{DRE} / \text{DRE (Base Case)}$	0.24 (0.97)	0.20 (0.39)	0.20 (0.56)	0.49 (2.4)

- Satellites currently achieve (**AT BEST**) DRE uncertainties of 2-3 Wm^{-2} , when constrained by particle properties measured by ground-based aerosol networks (Sherman and McComiskey, 2018).

II. Reductions in aerosol DRE by application of ground-based particle property measurements to constrain satellite-retrieved aerosol air mass type

- As part of a proposed strategy for reducing DRE uncertainty, Kahn et al. (2017) have the goal to acquire enough sub-orbital in situ measurements of aerosol optical and microphysical properties corresponding to major aerosol types to construct probability density functions (PDFs) of the key properties corresponding to each major aerosol air mass type.
- The PDFs can then be used to prescribe aerosol optical properties and calculate aerosol DRE at any location where satellites are able to successfully retrieve AOD and aerosol type (Kahn et al., 2017)
- Approach has many challenges (some discussed here) but also great potential to better constrain aerosol properties in satellite aerosol retrieval algorithm and estimates of aerosol DRE

III. How does MISR retrieve 'aerosol type'?

- Multi-angle Imaging Spectrometer (MISR), onboard the EOS Terra satellite, measures top-of-atmosphere (TOA) radiances (approximately weekly above a given site) at four wavelengths (446,558,672, and 866 nm) and nine viewing angles (Diner et al., 2008)
- For each 4.4km Level 2 pixel, MISR Version 23 aerosol retrieval algorithm (Diner et al., 2008) searches a database of TOA radiances simulated for the four instrument wavelengths, solar angle, and camera viewing angles, over 74 possible aerosol mixtures (Tables 1 and 2 of Kahn and Gaitley, 2015) and an array of AOD values.
- The algorithm then selects the combination(s) of simulated radiances that match measured TOA radiances to within a specified tolerance (Kahn et al., 2010), resulting in a set of self-consistent AOD and aerosol mixtures.
- The 74 aerosol mixtures are various relative contributions of 8 aerosol models, which differ in particle size (3 groupings), shape (spherical or non-spherical), and degree of absorption (non-absorbing, weakly-absorbing, strongly-absorbing)
- Since several of the 74 different aerosol mixtures in the MISR aerosol climatology can produce agreement with the MISR-measured TOA radiances to within radiometric resolution of the instrument (Diner et al., 2008), ***aerosol types retrieved by MISR are often ambiguous, especially for mid-visible AOD < 0.20***, which represents majority of cases in U.S. 😊
- MISR Version 23 aerosol product includes the following outputs, to help classify 'aerosol type'
 - (1) Mixture number of lowest residual aerosol mixture, along with other 'successfully-retrieved' mixtures
 - (2) For lowest residual mixture,
 - (i) fraction of AOD due to 'small' particles ($D < 700\text{nm}$), 'medium' particles ($700\text{nm} < D < 1400\text{nm}$), and 'large' particles
 - (ii) absorption AOD ($AAOD = \omega_0 * AOD$)
 - (iii) AOD due to spherical and non-spherical particles

Three levels of 'aerosol type' sensitivity are possible

- **Coarsest level** involves three types of particles: (1) spherical, non-absorbing; (2) spherical, absorbing; and (3) non-spherical (mainly dust).
- **'Medium' level of sensitivity** involves eight aerosol type bins, which represent different sizes within the three overall groupings, SSA values for absorbing particles, and non-spherical particle sizes (Kahn and Gaitley, 2015).

Group 1: Mixtures 1-10: Spherical, non-absorbing, 'smaller' particles

Group 2: Mixtures 11-20 Spherical, non-absorbing, 'medium' particles

Group 3: Mixtures 21-30 Spherical, non-absorbing, 'larger' particles

Group 4: Mixtures 31-40 Spherical, weakly-absorbing

Group 5: Mixtures 41-50 Spherical, absorbing

Groups 6-8: Mixtures 51-74 , Dust, with various absorption, size, and shape combinations

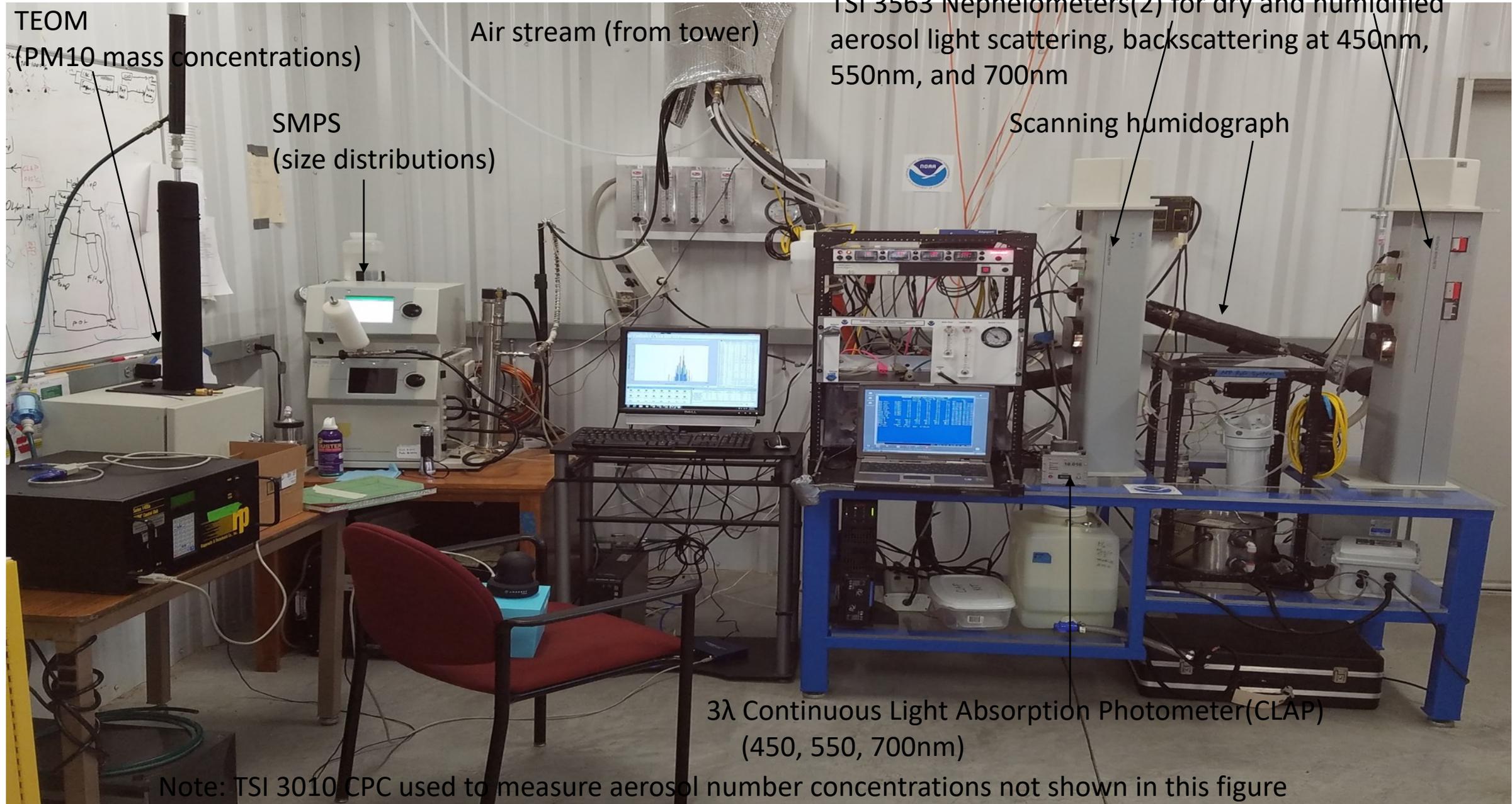
- The **highest level of sensitivity** involves the 74 individual aerosol mixtures in the MISR climatology, which differ in the relative contributions of the eight 'medium-resolution' aerosol groupings.
- Major challenge is inferring aerosol air mass types used by the atmospheric research community (ex: biomass burning, polluted continental, dust, clean continental...) from the 8 optically-constrained groups retrieved by MISR
- First-order aerosol air mass classification (Kahn and Gaitley, 2015), **based on the relative frequencies of the 8 medium level mixture groups**
ex: Clean continental (1,2,3 and/or 6,4), somewhat polluted (2,4,1), polluted or smoky (4,2,1), very polluted or smoky (5,,4,2,3) maritime (6,7,1), dusty (3,6,1)

IV. Constraining MISR aerosol air mass types through PDFs of in situ-measured aerosol properties-Opportunity for NOAA-ESRL Network?

- *The challenge of classifying MISR aerosol type in terms of the more commonly-associated aerosol air mass types (biomass burning, polluted continental, dust,...) usually necessitates additional information, which can be supplied by ground-based aerosol networks (mainly NOAA ESRL, collocated with AERONET or SURFRAD), along with air mass back-trajectories (ex: HYSPLIT)*
- In situ aerosol measurements needed to better identify and constrain the major aerosol air mass types inferred by MISR
- (1) **Aerosol size**: Size distributions or (if not available at network site) hemispheric backscatter fraction and sub-micron scattering fraction
- (2) **Aerosol absorption properties**: Spectral ω_0 (450, 550, 700nm for NOAA ESRL), calculated from scattering and absorption coefficient measurements
- (3) **Particle shape information**: Spherical or non-spherical particles inferred from lidar depolarization ratio or other
- (4) **RH-dependence of particle optical properties**: Measured by humidified light scattering and back-scattering at NOAA-ESRL sites. Critical for correcting the optical properties to ambient RH
- (5) **Aerosol chemistry**: Critical for source apportionment but \$\$\$\$\$. We currently have everything but this at APP.
- (6) **Aerosol mass scattering and extinction efficiencies**: Calculated from light scattering measurements (NOAA-ESRL), along with aerosol mass concentration measurements (APP and other sites with TEOMs). Needed by the modelers.

Important Caveat: The degree to which ground-based in situ aerosol measurements are representative of the column necessitates additional information (ex: vertical aerosol profiles measured by co-located lidar or inexpensive ceilometer)

In situ lower tropospheric aerosol instruments at Appalachian State Univ. (NOAA ESRL)



TEOM
(PM10 mass concentrations)

Air stream (from tower)

TSI 3563 Nephelometers(2) for dry and humidified aerosol light scattering, backscattering at 450nm, 550nm, and 700nm

SMPS
(size distributions)

Scanning humidograph

3λ Continuous Light Absorption Photometer(CLAP)
(450, 550, 700nm)

Note: TSI 3010 CPC used to measure aerosol number concentrations not shown in this figure

AppalAIR 2 field site- NASA AERONET, NASA MPLNET, NASA SolRadNET



Yankee Scientific
All-Sky Imager

Kipp & Zonen
Solar Pyranometer
(SolRadNET)

Cimel 318N
Sunphotometer
(Column-averaged
aerosol properties-
AERONET)

Micro-pulsed lidar
(Vertical aerosol and
cloud profiles-
MPLNET)

Note: A TEOM used to measure PM_{2.5} mass concentrations is housed in a small data acquisition control building, located just to the left of the All-sky Imager (not shown in the figure)

V. Method for evaluating/constraining MISR-retrieved aerosol type

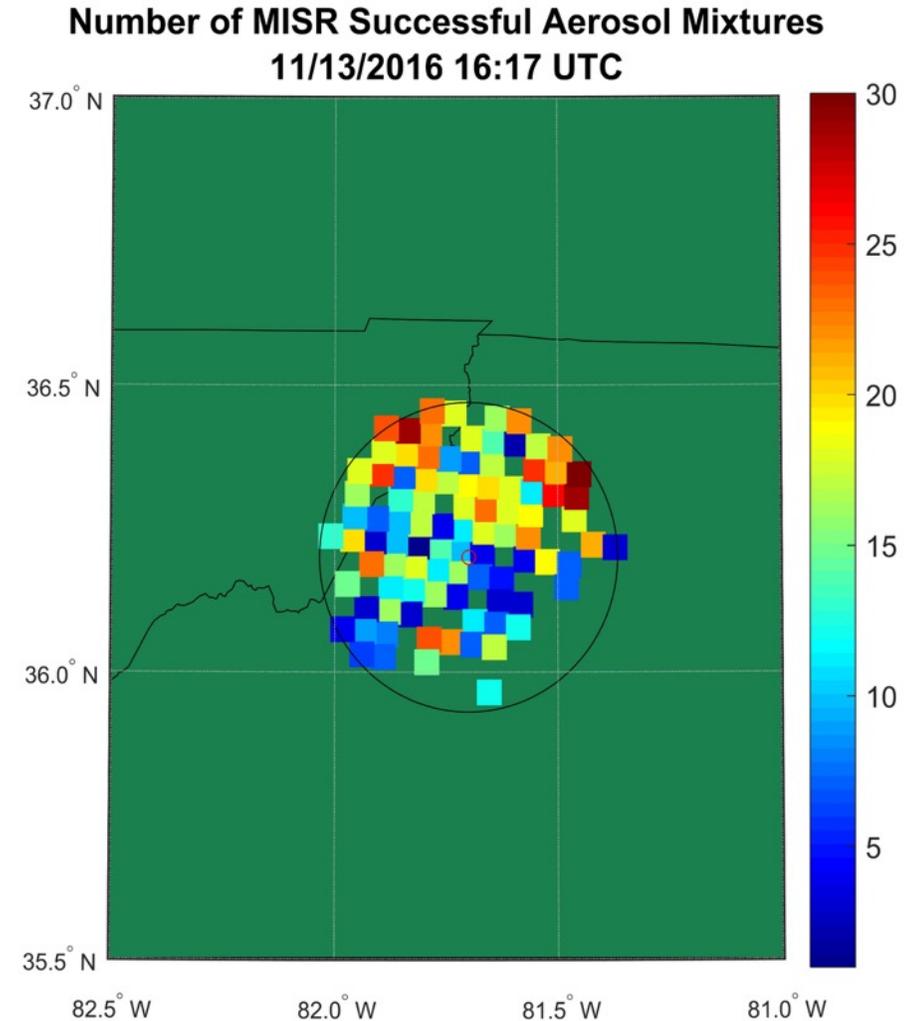
For each MISR overpass day with any successful aerosol retrievals within a representative radius of the site (ex: ~30km for APP),

- **Step 1:** Extract the following MISR variables for each 4.4km pixel lying within the representative geographic radius

- (1) Mixture number for lowest residual mixture;
- (2) Mixture numbers for all successfully retrieved mixtures;
- (3) AOD at 558nm (related to mean AOD of successful aerosol mixtures)

Along with the following properties, corresponding to the lowest residual mixture

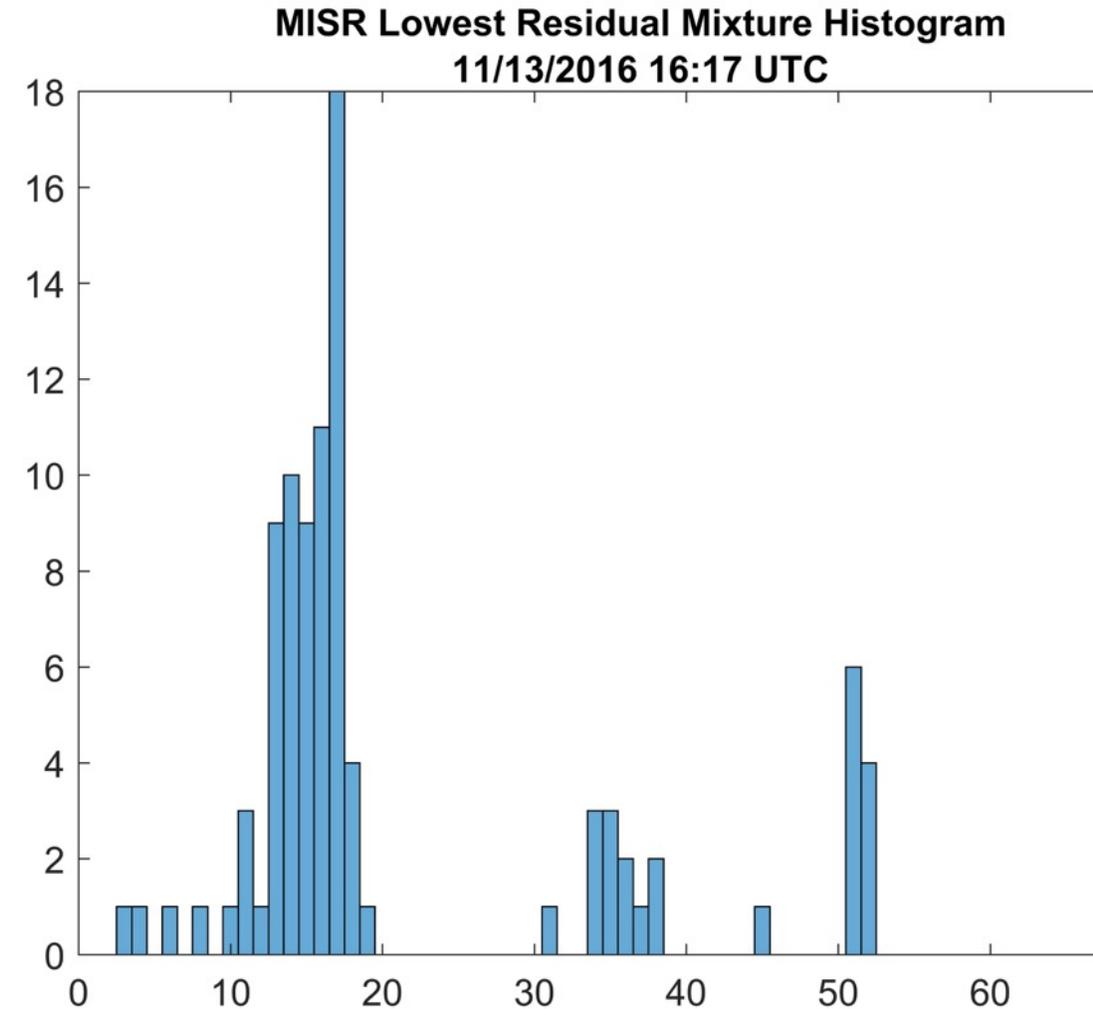
- (4) AOD due to small, medium, and larger particles;
 - (5) AOD due to spherical and non-spherical particles; (iii)
 - (6) Absorption AOD ($AAOD = \omega_0 * AOD$)
- **Step 2:** Discard the aerosol data (Step 1) for pixels with more than ~20- 30 successfully-retrieved aerosol mixtures (inability to discern aerosol type).
 - IF sufficient number of pixels remain, continue to Step 3



Sample MISR day- Western NC wildfires
November 13, 2016

Method for evaluating/constraining MISR-retrieved aerosol type (continued)

- **Step 3:** Place the lowest residual mixtures numbers for each pixel into bins (8-for medium-level classification) of similar aerosol properties
 - Group 1: Mixtures 1-10: Spherical, non-absorbing, smaller particles
 - Group 2: Mixtures 11-20 Spherical, non-absorbing, medium particles
 - Group 3: Mixtures 21-30 Spherical, non-absorbing, larger particles
 - Group 4: Mixtures 31-40 Spherical, weakly-absorbing
 - Group 5: Mixtures 41-50 Spherical, absorbing
 - Groups 6-8: Mixtures 51-74 , Dust, with various absorption, size, and shape combinations
- **Step 4:** Classify 'aerosol type' by the relative frequencies of the 8 medium resolution aerosol groups.
- Example: On 11/13/2016, group 2 (spherical, non-absorbing medium particles) was most frequently-retrieved, followed by group 4 (spherical, weakly-absorbing) and then group 6 (dust)



Method for evaluating/constraining MISR-retrieved aerosol type (continued)

- **Step 5:** Convert the retrieved ‘aerosol type’ in step 4 to more useful aerosol air mass type, which may be re-classified after more information is known (ex: a known aerosol source on that day, in situ aerosol properties, and/or back-trajectories)
- For example, the highest occurrences of groups 2 and 4 could fall under the air mass classifications (Kahn and Gaitley, 2015) of ‘somewhat polluted’ or ‘polluted or smoky’
- **Step 6:** Use the in situ–measured aerosol properties (along with any known aerosol sources on that day and/or back-trajectories) to better classify aerosol air mass type

Aerosol Property	Hourly-averaged value(s) during MISR overpass	Information obtained
ω_0 at 450,550, 700nm	0.95, 0.95,0.95	Particles highly reflective
Scattering hygroscopic growth factor $f(\text{RH}) = \sigma_{\text{sp}}(\text{RH}=85\%) / \sigma_{\text{sp}}(\text{RH}=40\%)$	$f(\text{RH})=1.13$	Particles largely hydrophobic
Absorption Angstrom exponent (450nm/700nm)	$A_{\text{ap}}=2.0;$	Consistent with biomass burning or dust
Sub-1 μm scattering fraction and scattering Angstrom exponent (450nm/700nm)	$R_{\text{sp}}=0.86$ $A_{\text{sp}}=2.0;$	Scattering dominated by particles with $D < 1\mu\text{m}$ (rules out dust)
Hemispheric backscatter fraction at 550nm	$b=0.12$	Indicative of ‘medium-size’ sub-micron particles
Geometric-mean particle size by number and volume (from size distribution measurements)	91nm (number-weighted) 310nm (volume weighted)	

Method for evaluating/constraining MISR-retrieved aerosol type (continued)

- **Step 7:** Use in situ measurements (and back-trajectories) to re-classify aerosol airmass type
- Even without the obvious knowledge of fire influence on this day (from known source and HYSPLIT back-trajectory), the in situ measurements indicate a high likelihood that the aerosol air mass type is 'biomass burning'. The highly reflective nature of the particles also is indicative of aged smoke.

Note: On most examined days to date, all information is needed

- **Step 8:** Append the in situ aerosol properties to the appropriate air mass type (biomass burning for this day) to 'build up statistics' for the PDFs

VII. Conclusions, challenges and future work

- There exists a unique opportunity for NOAA-ESRL sites equipped with some ancillary measurements (ex: sunphotometers, lidar or ceilometer, size distributions, aerosol hygroscopicity) to **COLLECTIVELY** contribute to improvements in satellite-based aerosol retrievals necessary for improving DRE estimates and (ideally) chemical transport models
- That being said, there are many challenges, including (so far)
 - (1) difficulty in classifying optically-constrained aerosol type in terms of aerosol air mass types useful for modeling and air quality studies
 - (2) Lack of MISR overpasses and (at least over mountainous region near APP) retrievals. Most high-loading days were missed. This illustrates need for multiple sites and/or very long data records
 - (3) A given site likely will only sample a few (at most) of the major aerosol air mass types with enough frequency to develop statistically-reliable PDFs.
- These challenges represent opportunities for collaboration amongst network sites, which are home to various aerosol air mass types and loading levels
- Once PDFs developed, we will conduct comparison of DRE calculated using satellite data products (with aerosol type constrained by PDFs) with that calculated based on aerosol network properties measured at APP (and other ESRL sites??)

Thanks for staying awake.....if you stayed awake!



Acknowledgements

- APP is the only co-located NOAA ESRL, NASA AERONET, and (active) NASA Micro-pulsed lidar network site in the U.S., while relying solely on undergrad and MS students (i.e. no devoted technical staff or PhD students)
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