Long-term aerosol measurements at Appalachian State University (Boone, NC USA) for improved understanding of relationships between changing regional air quality and climate

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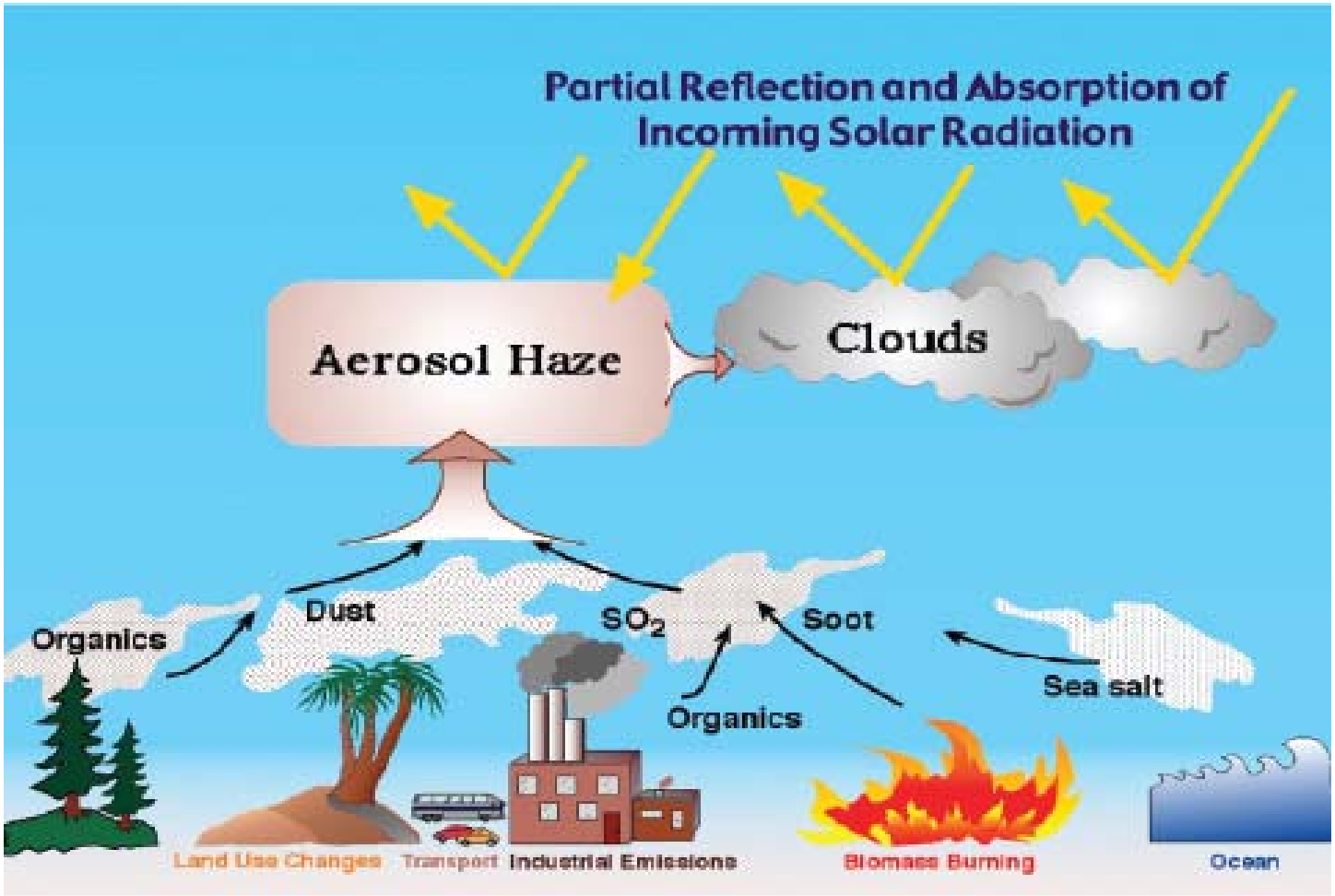
Talk Outline

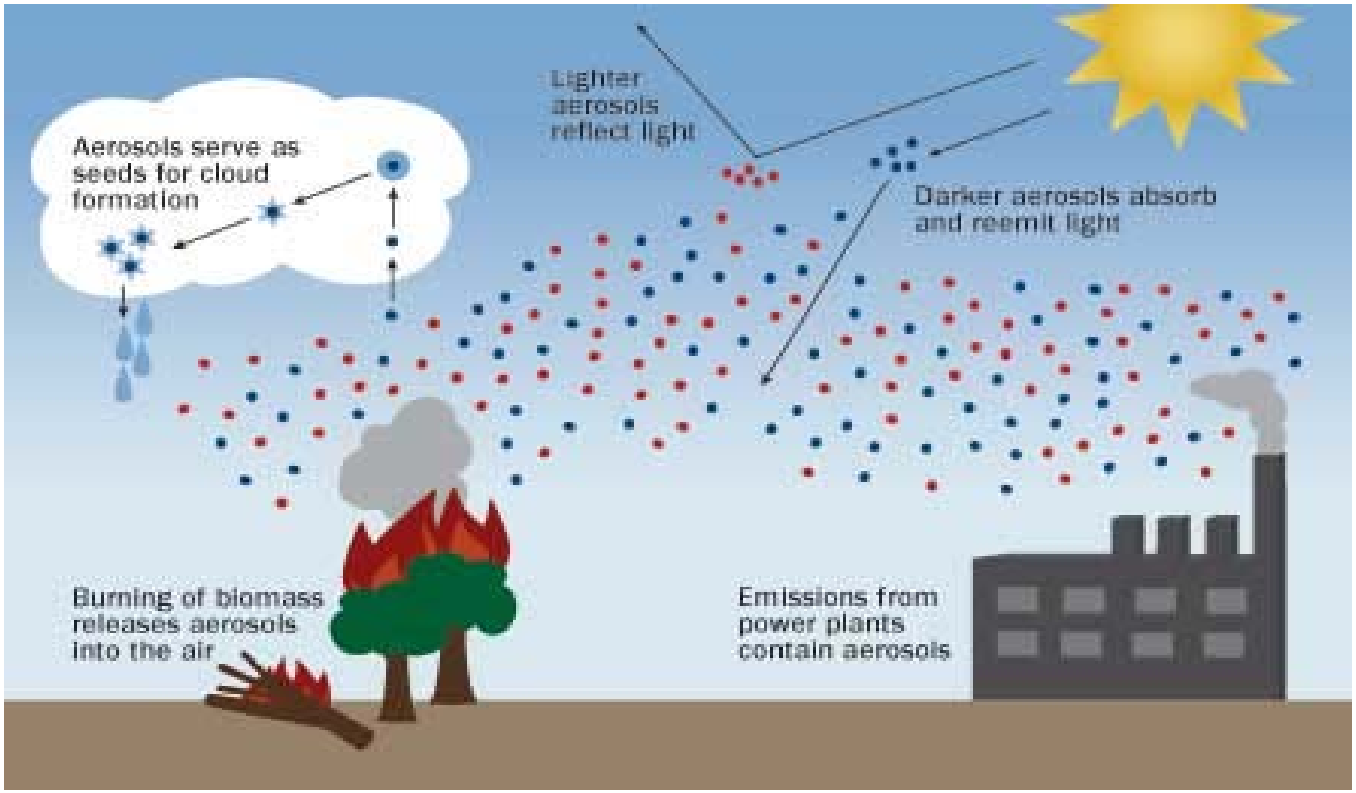
I. What are atmospheric aerosols and why is it important to study them in SE U.S?
II. NOAA and NASA aerosol network sites at APP State
III. Ancillary Measurements
IV. Sample of Data Products
V. Conclusions and Future Work
VI. Appendix-More data samples

I. What are aerosols and how do they affect climate?



Aerosols are tiny suspended particles (ranging from a few nm to several microns in size) originating from a variety of natural and anthropogenic sources. They are often observed as dust, smoke, and haze

Aerosol effects on solar radiation

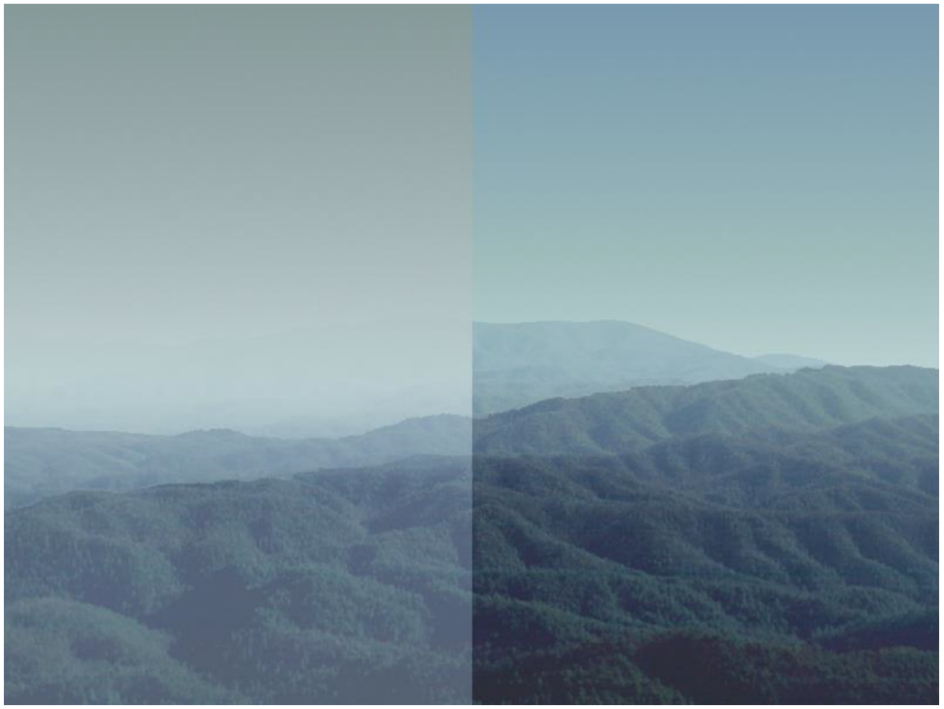


- Aerosols ***directly*** affect the amount of solar radiation reaching earth's surface by scattering and absorbing solar radiation (aerosol direct radiative effect-DRE) and ***indirectly*** affect the amount of solar radiation by affecting cloud reflectivity, amounts, and lifetimes.

Aerosol radiative effect-The means for quantifying aerosol effects on solar radiation budget

- In addition to their effects on air quality (visibility, human health), aerosols modify solar radiation at top of atmosphere and at surface, which in turn modifies weather and climate
- Aerosol radiative effect is the difference in the net flux of solar radiation (downwelling minus upwelling) in the presence of aerosols, minus the net flux in absence of aerosols
- Units: Watts per square meter (W / m2)
- This talk will only deal with direct radiative effect (DRF) due to scattering and absorption of sunlight by aerosols in absence of clouds
- Positive (negative) aerosol DRE is associated with warming (cooling effect)
- Aerosols usually reduce net down-welling solar flux (negative DRE) at top of atmosphere (TOA) and always reduce it at the surface
- However, short aerosol atmospheric lifetimes (3-10 days) and highly inhomogeneous source distributions make them very difficult to quantify
- ***Uncertainties in radiative forcing by aerosols represent the largest uncertainties in climate models used to predict future temperature trends (IPCC 2013)***

I. Background: Relevance of aerosol direct radiative forcing studies in southeastern US



- Southeastern US is home to high (**BUT DECREASING**) warm-season levels of sulfate and biogenic secondary organic aerosol and is one of only a few regions not to have warmed in 20th century
- Simulated mean visibility for 20% of haziest days annually at Great Smoky National Park in 1990 (left) and 2011(right).
- Figure from Hand, et al. *Widespread reductions in haze across the United States from the early 1990s through 2011 2014*, Atmos. Env, 2014
- ***Could improved air quality in eastern US contribute to regional warming????***
- Ground-based aerosol network measurements of aerosol radiative properties and DRE are of particular importance over mountainous terrain, often home to high levels of biogenic aerosols and where the satellite-based retrievals often suffer; yet there are very few such sites in the region
- ***Appalachian State University (APP) is home to the only co-located NOAA-ESRL, NASA AERONET, and (active) NASA MPLNET sites in the U.S.,*** with datasets (except the MPLNET) approaching 9 years that can be used for DRE trend studies, validation of satellite-based aerosol retrievals, and evaluation of models
- APP is also a World Meteorological Organization Global Aerosol Watch site (WMO GAW), with data submitted to World Data Centre for Aerosols

Aerosol studies at APP

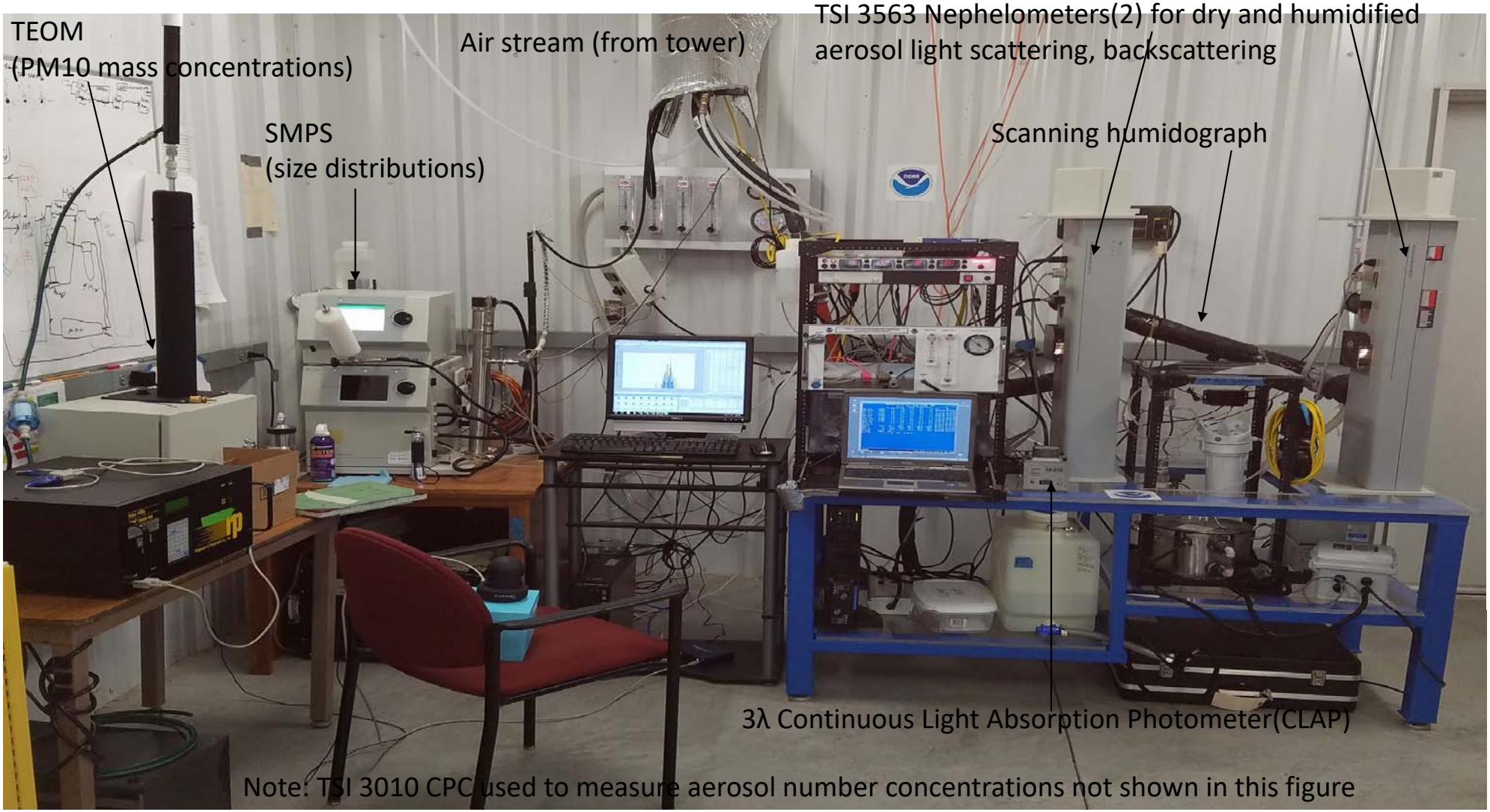
3 primary research objectives:

- ***Validate/evaluate NASA satellite-based aerosol retrievals over mountainous regions***, where satellites typically perform poorly (Levy et al., 2010; Sherman et al., 2016)
- ***Quantify effects of changing regional air quality on aerosol radiative properties and direct radiative effect (DRE)***. Satellite aerosol retrievals not capable of even close to the 1 W / m2 uncertainty needed to better quantify aerosol DRE
- ***Increase spatial coverage of aerosol measurements in mountainous U.S. and African regions***: Network of handheld sunphotometers (designed, developed, tested, and calibrated at APP) was initiated in June 2017. The sunphotometers are used by Citizen Scientists (often university students) at mountainous locations in U.S. and sub-Saharan Africa (**N**orth American and sub-Sahara African Mountain Aerosol Network; NASA MAN) to help satisfy the first two research objectives

NOAA ESRL site

- 34m aerosol sampling tower for in situ aerosol measurements (next slide), situated well-above the tree line
- Meteorological station (T,P,RH measurements) and gas sampling lines also at top of tower

In situ lower tropospheric aerosol instruments (NOAA ESRL)



S1

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 PM2.5 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)

Slide 10

S1 Shermanjp, 9/1/2017

Data Product	Measurement Technique
Aerosol hygroscopic growth: total light scattering & hemispheric backscattering (450nm, 550nm, 700nm)	TSI 3563 Nephelometer operating at a reference RH (≤40%) in series with a second scanning TSI 3563 (40%-90% RH)
Aerosol light absorption (corrected to 450nm, 550nm, 700nm)	Continuous Light Absorption Photometer (CLAP), developed by NOAA ESRL
Aerosol number concentrations Aerosol mass concentrations (PM 10, PM2.5)	TSI 3783 Environmental Particle Counter and TSI 3760 Condensation Nuclei Counter Thermoscientific 1400 Particulate Matter Monitors (2), one with 10-micron inlet and one with 2.5 micron inlet
Aerosol size distributions	TSI Scanning Mobility Particle Sizer (SMPS)
Aerosol chemical composition (size-resolved, sub-um)	Aerodyne Quadrupole Time-of-Flight Aerosol Mass Spectrometer (only during summers 2012-2013, winter 2013)

Data Product	Measurement Technique
Aerosol Spectral Optical Depth at 8 wavelengths (340,380,440,500,675,870,1020, and 1640nm) Total, coarse, and fine mode components derived	CIMEL 318-EBN Sun/Sky Radiometer
Precipitable water vapor	CIMEL differential extinction 870/936nm
Aerosol size distributions, single-scattering albedo	1. CIMEL sky radiance measurements (principle plane and almucantor scenerios) 2. Scanning mobility particle sizer (SMPS; for PM1 aerosol only)
Total broadband irradiance (direct plus diffuse)	Kipp and Zonen CMP22 Pyranomter
Cloud optical depth and cloud fraction	CIMEL and Yankee Scientific TSI-440 All-sky Imager

Data Product	Measurement Technique
Vertical profiles of (a) aerosol normalized relative backscatter (NRB) and (b) aerosol extinction coefficient at 532nm, along with aerosol optical depth (AOD)	Sigma Space MPL-4B Micro-pulsed Lidar (MPL)
Boundary layer heights	Derived using Sigma Space MPL-4B Micro-pulsed Lidar (MPL)
Cloud base heights	Sigma Space MPL-4B Micro-pulsed Lidar (MPL)
Surface meteorology (T, P, RH, winds)	2 MET stations -APP, Beech Mountain (colleague Baker Perry)
Vertical meteorology (T, P, RH, winds)	InterMET Radiosonde Launching System (Perry, Sherman, students)

North American and sub-Sahara African Mountain Aerosol Network (NASA MAN)

- Handheld sunphotometers used to measure aerosol optical depth(at 4 visible and near-IR wavelengths) and precipitable water are designed and constructed at APP State. Instruments are calibrated and evaluated against the NASA AERONET sunphotometer at APP. Measurements initiated at APP in 2010
- Primary research objective is to deploy inexpensive (~$500) instruments to evaluate satellite-based aerosol retrievals and for air quality studies at mountainous U.S. and African sites
- African measurements initiated at Botswana International University of Science and Technology (BIUST) in June 2018. Faculty at 3 Ethiopian universities received instrument training and will begin measurements at their universities in fall 2018
- Measurements at University of Utah will commence in fall 2018.
- Data from initial network sites will be leveraged into grant proposals to expand the network to include other mountainous U.S. and African sites

III. Sample Data Products

A. Long-term time series of aerosol radiative properties-Changing regional air quality and possible future implications for aerosol direct radiative effect

B. Seasonal variability in aerosol direct radiative effect

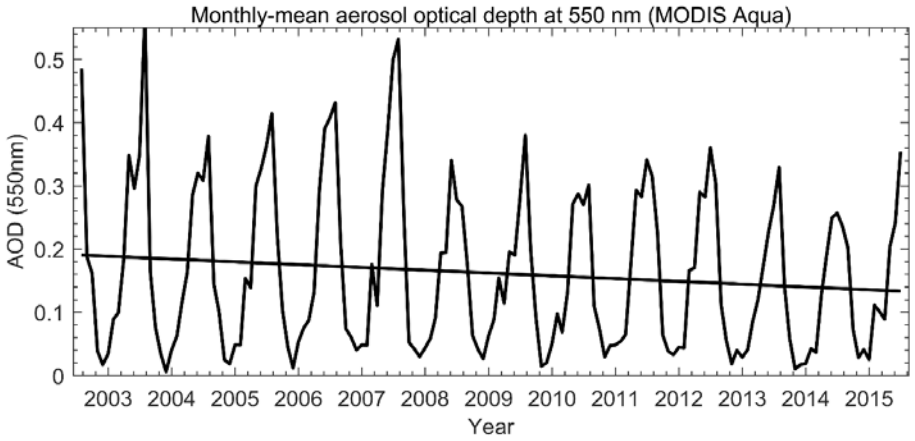
C. North American and sub-Sahara African Mountain Aerosol Network (NASA MAN)

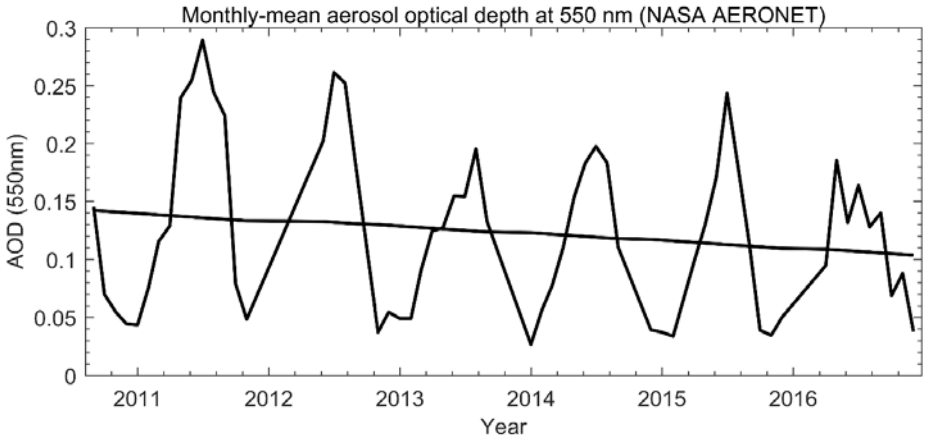
D. Aerosol chemistry during 2012-2013 (measured by APP undergrad Michael Link)

Sub-micron aerosol chemical composition: Measured by AMS during summers 2012-2013 and winter 2013 by former APP undergraduate student Michael Link

A. Long-term time series of aerosol radiative properties-Changing regional air quality and possible future implications for aerosol direct radiative effect

Aerosol Optical Depth (AOD) from MODIS Aqua and APP AERONET site

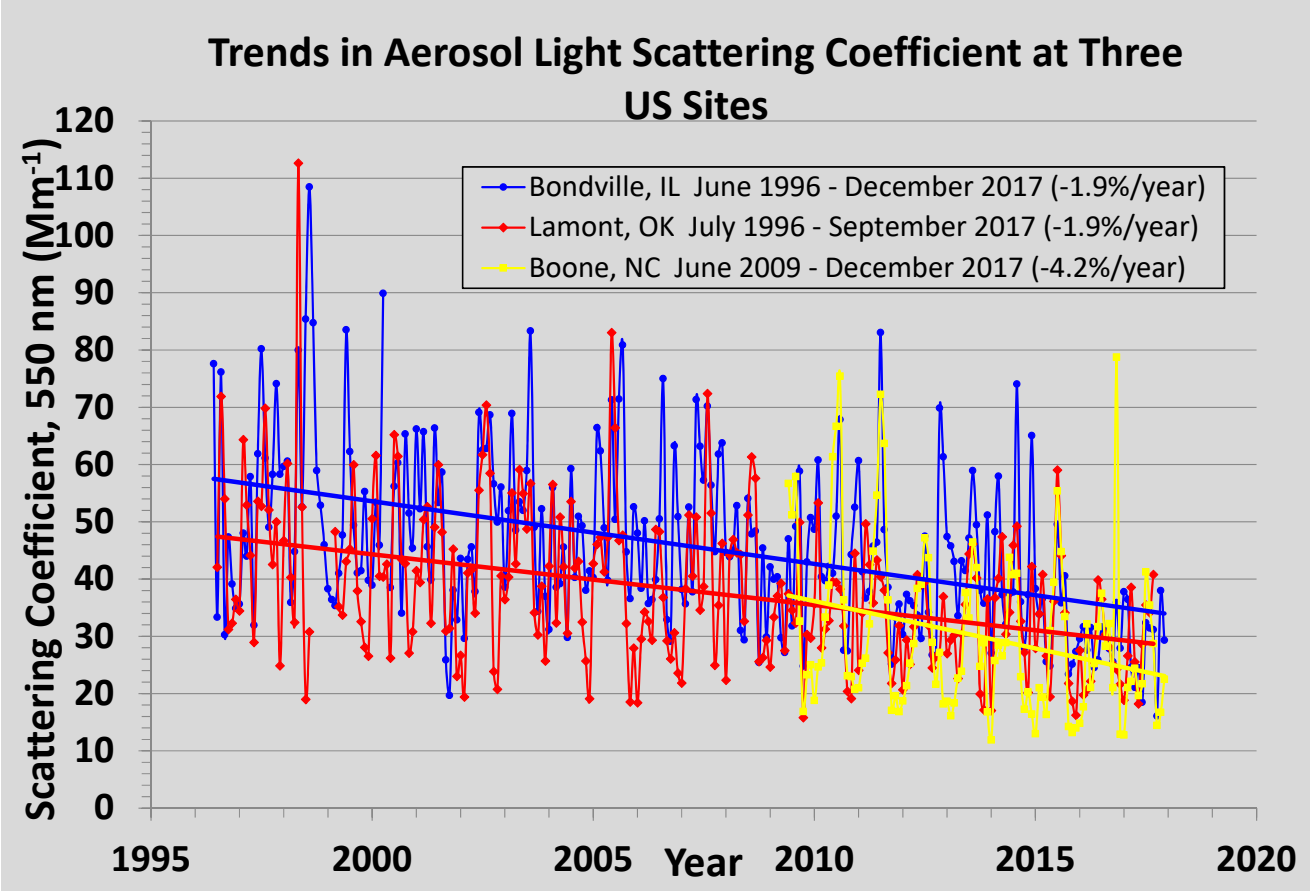




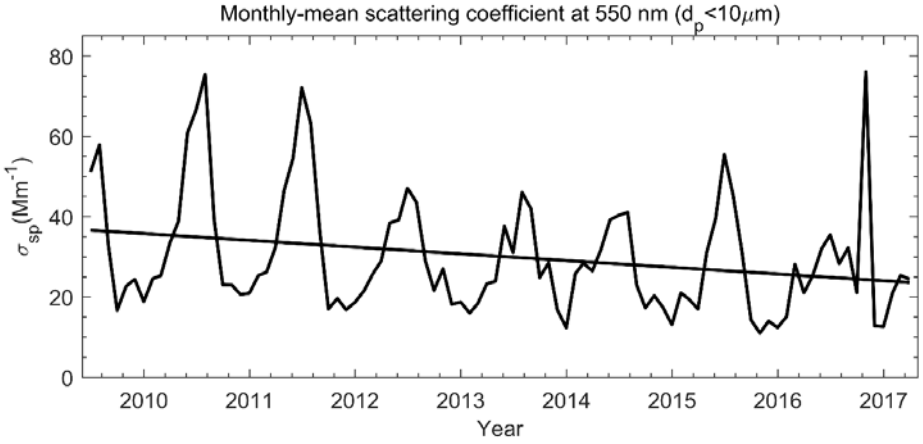
- Decreasing AOD trends in eastern U.S reported in other studies (Alston and Sokolik, 2016; Yoon et al., 2011….)
- Since DRE is most sensitive to AOD, this likely implies that DRE is becoming less negative (smaller cooling effect)

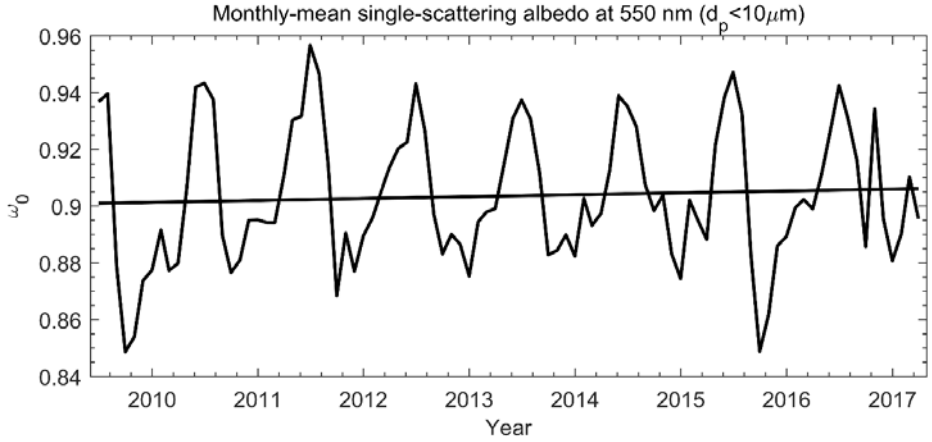
Long-term (~9 yrs) changes in aerosol light scattering, absorption, and their relative contributions (from NOAA-ESRL measurements)

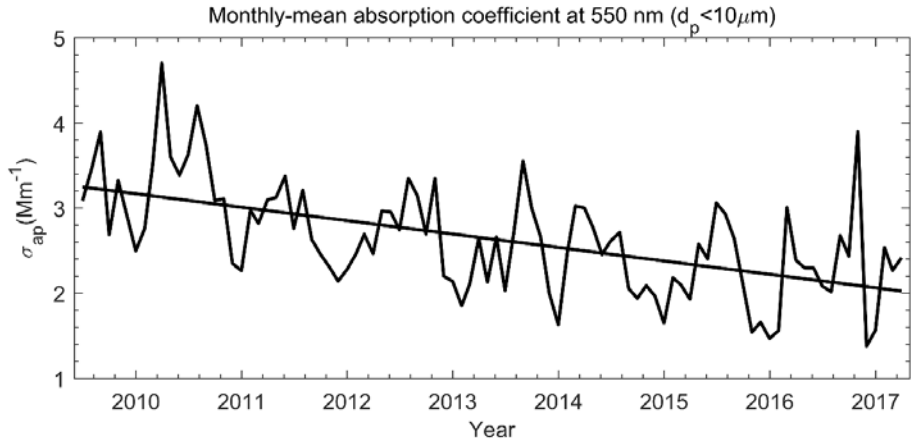
- Decreases in aerosol light scattering in eastern U.S. largely attributed to reductions in power plant emissions (SO2)
- Similar decreases in aerosol light absorption (next slide) largely due to reductions in black carbon emissions (from diesel, etc..)



Long-term (~9 yrs) changes in aerosol light scattering, absorption, and their relative contributions

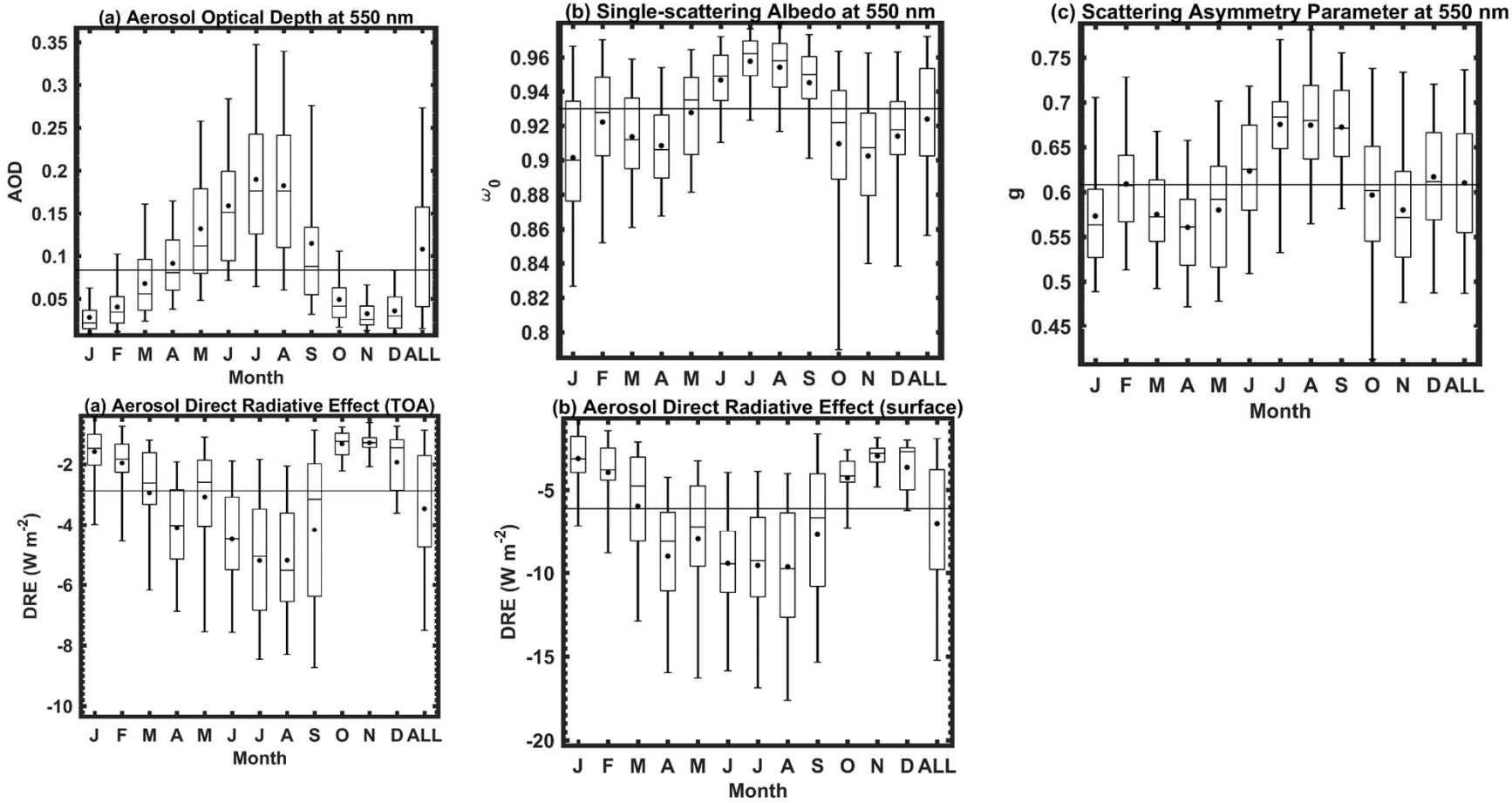






- Aerosol light scattering and absorption are decreasing at similar rates, leading to very small (if any) changes in single-scattering albedo
- The time series is modulated by months with influence from wildfires (June 2016, November 2017)

B. Seasonal variability in aerosol optical properties and direct radiative effect

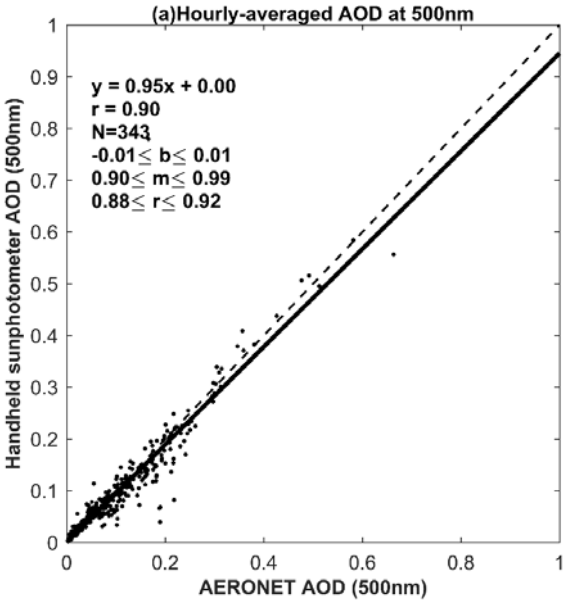


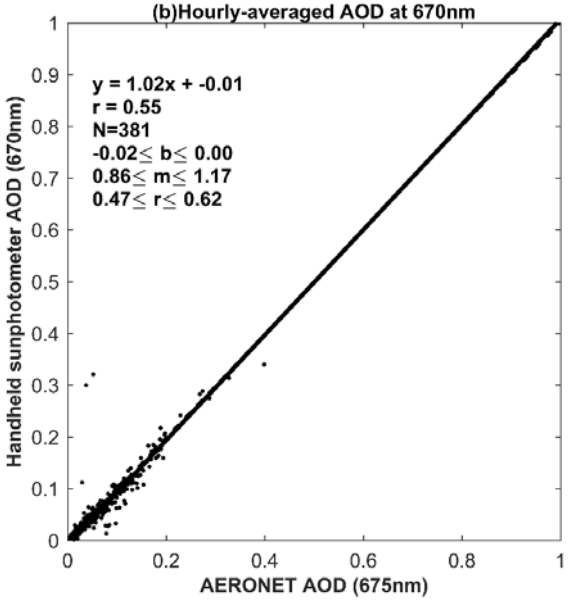
Aerosol optical depth at APP is ~9-10 times larger during summer than during winter. It is accompanied by higher single scattering albedo (more reflective particles) and higher asymmetry parameter (larger sub-micron particles), consistent with sulfates and SOA.

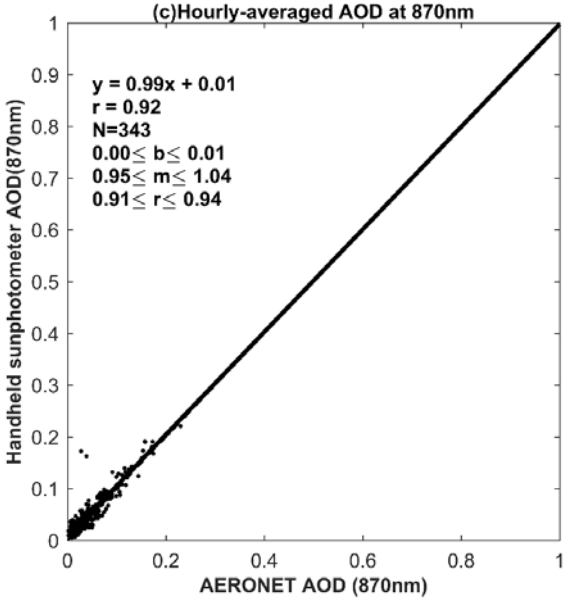
Aerosol DRE annual cycle (calculated using SBDART radiative transfer model) follows that of AOD. Figures from Sherman and McComiskey, 2018.

C. North American and sub-Sahara African Mountain Aerosol Network (NASA MAN)

- A 6-year comparison of aerosol optical depth (AOD) measured by the prototype handheld sunphotometer with AOD measured at the APP State AERONET site was conducted to estimate instrument AOD measurement capability
- AOD uncertainties of ~0.01-0.02 are 3-5 times less than current satellite capabilities and affirm the capability of the handheld sunphotometers for satellite validation and air quality studies
- One limitation is that the lack of days with high AOD to better characterize instrument performance in highly polluted environments
- Instrument precision will be evaluated (fall 2018), based on simultaneous AOD measurements made by 5 handheld sunphotometers in Botswana during summer 2018

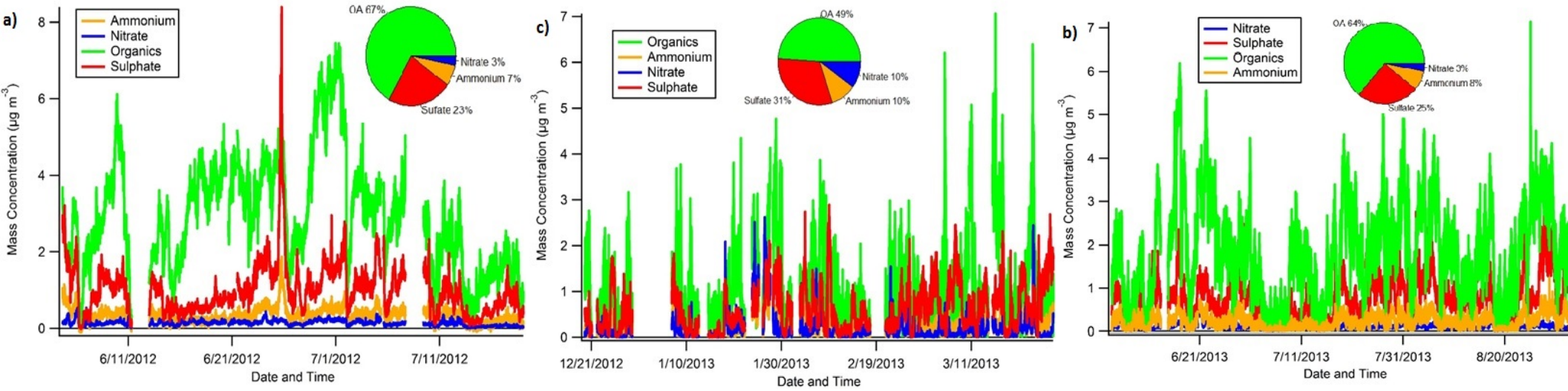






D. Sub-micron aerosol chemical composition

- Studies conducted using an AMS by former Chemistry researcher Dr. Yong Zhou and former ASU Chemistry undergrad Michael Link during summers 2012-2013 and winter 2013 (Link et al., 2015)



Above figures are from the Supplement to **Link, M.F**., Zhou,Y., Taubman, B.F., Sherman, J.P., Sive, B.C., Morrow,H., Krintz, I., Robertson,L., Cook, R., Stocks, J., West, M, and Sive, B..: A characterization of volatile organic compounds and secondary organic aerosol at a mountain site in the Southeastern United States , J. Atmos. Chem, 01/2015; DOI:10.1007/s10874-015-9305-5, 2015.

V. Conclusions and Future Work

- The NOAA and NASA-supported aerosol monitoring sites (along with measurements of PM, clouds, solar radiation, etc) at APP provide a long-term, continuous dataset to improve understanding of interactions between changing regional air quality, weather, and climate
- The NASA MAN network of low-cost aerosol sensors has the capability for expanding geographic coverage to regions in U.S. and Africa devoid of aerosol measurements. If funding sources can be identified, this could include NC
- Decreased aerosol loading at APP over past ~9 years is consistent with other studies conducted over the eastern U.S. (based primarily on satellite measurements and field campaigns) Trend studies will be possible in the next 1-2 years, as datasets reach the ~10 year threshold for such studies
- A major question is "Will improved air quality lead to SE regional warming????"
- Current and future work includes (1) detailed satellite aerosol validation studies over APP, along with other mountainous U.S. and African regions; (2) trends in aerosol loading and direct radiative effect; (3) expanding the NASA MAN network (subject to procurement of external funding)
- APP aerosol data is publically-available at the NASA Micro-pulsed lidar MPLNET), NASA Aerosol Robotic Network (AERONET), and NOAA Earth System Research Laboratory (ESRL) websites, in addition to the NILO database (as part of WMO GAW). Links to these sites provided on next slide. →
- If interested in other data (PM, other measurements), please contact me at shermanjp@appstate.edu
- Collaborations are welcome. Please email me if interested.

- Thanks for staying awake ☺

Accessing APP Aerosol Data

- Lower tropospheric aerosol measurements as part of NOAA-ESRL

https://www.esrl.noaa.gov/gmd/aero/net/

- Column-averaged aerosol measurements (Aerosol Optical Depth, etc)
- https://aeronet.gsfc.nasa.gov/cgi-bin/webtool_aod_v3?stage=3&region=United_States_East&state=North_Carolina&site=Appalachian_State&place_code=10&if_polarized=0

- Vertically-resolved aerosol and cloud profiles

- https://mplnet.gsfc.nasa.gov/data?v=V3

- World Data Centre for Aerosols database (managed by NILO)
- https://www.gaw-wdca.org/ and
- http://ebas.nilu.no/default.aspx

- For other data (PM, solar radiation, cloud fraction, etc) , contact shermanjp@appstate.edu

Acknowledgements

The aerosol sites at APP and the resulting data products would not be possible without the help of MANY people, including

- Michael Hughes-APP State College of Arts and Sciences Electronic Technician
- Dana Greene-APP State College of Arts and Sciences Electronic Technician
- APP State College of Arts and Sciences (Neva Sprecht-dean)
- NOAA-ESRL and NASA AERONET staff
- The ~30 student researchers, who provided invaluable help with instrument maintenance, software development, and data analysis

Some recent publications using APP aerosol data

- Sherman, J. P. and McComiskey, A.: Measurement-based climatology of aerosol direct radiative effect, its sensitivities, and uncertainties from a background southeast U.S. site, Atmos. Chem. Phys., 18, 4131-4152, 2018 https://doi.org/10.5194/acp-18-4131-2018
- Andrews, E., Sheridan, P.J., Ogren, J.A., Hageman, D., Jefferson, A., Wendell, J., Alastuey, A., Alados-Arboledas, L., Bergin, M., Ealo, M., Hallar, A.G., Hoffer, A., Kalapov, I., Keywood, M., Kim, J., Kim, S., Kolonjari, F., Labuschagne, C., Lin, N., Macdonald, A.M., Mayol-Bracero, O.L., McCubbin, I.B., Pandolfi, M., Reisen, F., Sharma, S., **Sherman, J.P.**, and Sorribas M. : Overview of NOAA/ESRL's Federated Aerosol Network, BAMS-D-17-0175, accepted by *Bulletin of the American Meteorological Society*, July 2018.
- Schmeisser,L., E. Andrews, J.A. Ogren, P. Sheridan, A. Jefferson, S. Sharma, J.E. Kim, J.P. Sherman, M. Sorribas, I. Kalapov, T. Arsov, C. Angelov, O. Mayol, C. Labuschagne, S.-W. Kim, A. Hoffer, N.-H. Lin, M. Bergin, J.Y. Sun, P. Liu, and H. Wu (2017), Classifying aerosol type using in-situ surface spectral aerosol optical properties, Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2017-38.
- Sherman, J.P., Gupta, P., Levy, R.C., and Sherman, P.: An evaluation of MODIS-retrieved aerosol optical depth over a mountainous AERONET site in the southeastern US, Aerosol Air Qual. Res., 16, 3243–3255, doi: 10.4209/aaqr.2015.09.0568, 2016.
- Sherman, J.P., Sheridan, P.J., Ogren, J.A., Andrews, E.A., Schmeisser, L., Jefferson, A., and Sharma, S.: A multi-year study of lower tropospheric aerosol variability and systematic relationships from four North American regions, Atmos. Chem. Phys., 15, 12487-12517, doi:10.5194/acp-15-12487-2015, 2015.
- Link, M.F., Zhou,Y., Taubman, B.F., Sherman, J.P., Sive, B.C., Morrow,H., Krintz, I., Robertson,L., Cook, R., Stocks, J., West, M, and Sive, B. (2015), A characterization of volatile organic compounds and secondary organic aerosol at a mountain site in the Southeastern United States, J. Atmos. Chem, 01/2015; DOI:10.1007/s10874-015-9305-5, 2015.
- Kelly, G.M., B.F. Taubman, L.B. Perry, P.T. Soulé, J.P. Sherman, and P. Sheridan (2012), Relationships between aerosols and precipitation in the southern Appalachian Mountains. *International Journal of Climatology*, 33: 3016-3028. DOI: 10.1002/joc.3632, 2012.

VI. Appendix-More data samples

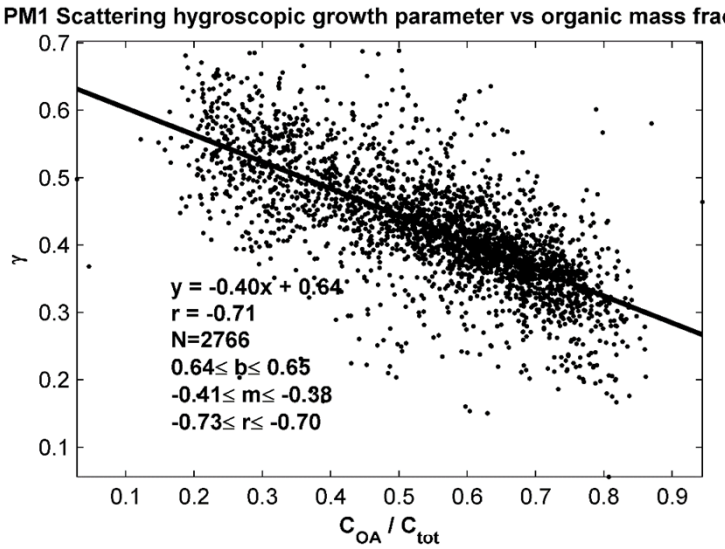
- The following slides contain various aerosol data products and results from studies

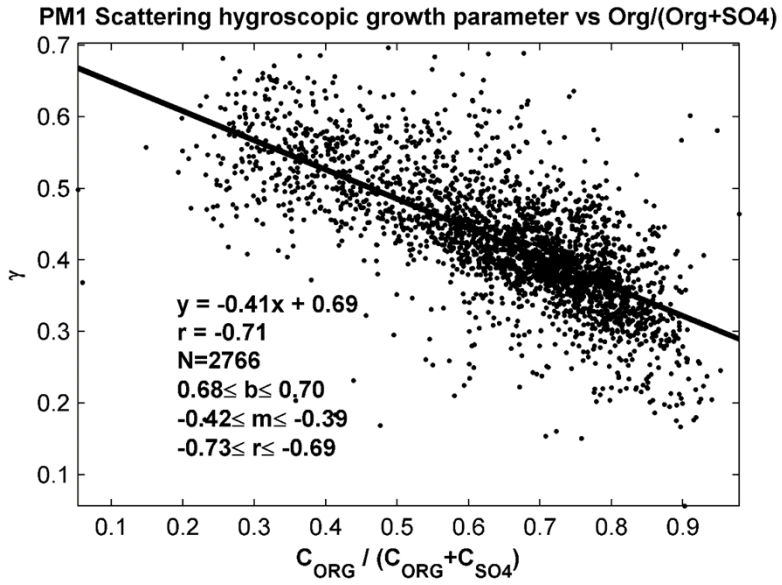
Uncertainties in DRE calculated from the ground-based and satellite-based aerosol measurements

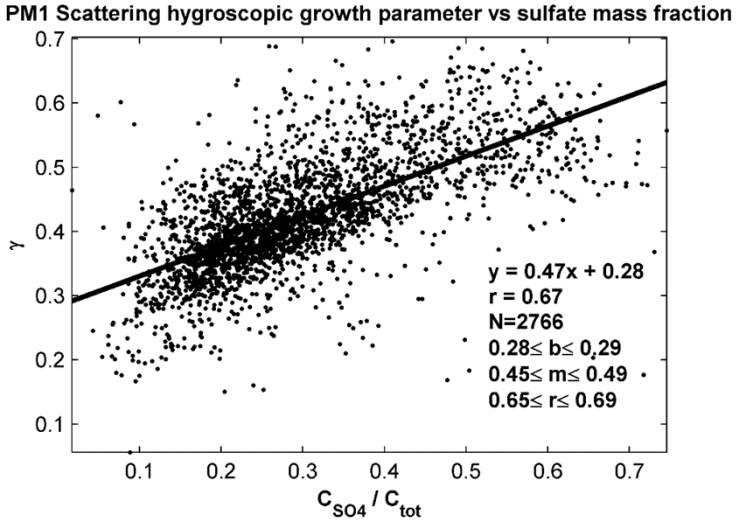
- Ground-based measurement uncertainties for APP site are (i) ΔAOD~0.01; Eck, 1999; (ii)ΔSSA~0.015 and Δg~0.01 ; Sherman et al., 2015; and ΔR~0.02; calculated based on Vermote, 2009.
- Calculated measurement uncertainties in DRE **at the TOA** and **at the surface.** Units of ΔDRE are W m^{-2}. The uncertainties associated with AOD are calculated twice; once using AERONET AOD uncertainties and once using the lower bound of MODIS or MISR AOD uncertainty ~0.05 (shown in parentheses).

	MAR	JUN	SEP	DEC
TOA ΔDRE_{AOD}	0.47 (2.3)	0.35 (1.8)	0.34 (1.7)	0.43 (2.1)
TOA $\Delta DRE_{\omega 0}$	0.14	0.58	0.27	0.039
TOA ΔDRE_{g}	0.059	0.18	0.12	0.018
TOA ΔDRE_{R}	0.023	0.084	0.034	0.0050
TOA ΔDRE	0.50 (2.3)	0.90 (2.1)	0.64 (2.0)	0.44 (2.1)
TOA ΔDRE / DRE (Base Case)	0.20 (0.96)	0.16 (0.36)	0.18 (0.54)	0.48 (2.4)
Surface ΔDRE_{AOD}	0.90 (4.5)	0.69 (3.5)	0.61 (3.0)	0.79 (3.6)
Surface $\Delta DRE_{\omega 0}$	0.23	0.80	0.45	0.064
Surface ΔDRE_{g}	0.061	0.19	0.12	0.019
Surface ΔDRE_{R}	0.019	0.069	0.036	0.0050
Surface ΔDRE	0.93 (4.5)	1.1 (3.6)	0.77 (3.1)	0.72 (3.6)

Scattering hygroscopic growth parameter versus organic and sulfate mass fractions





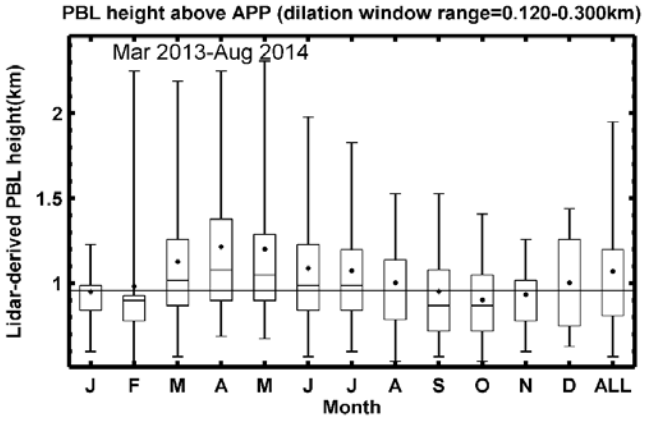


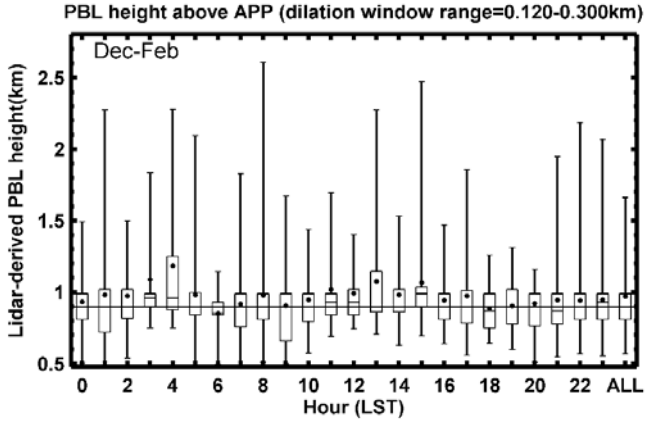
- Our linear model above is not much different than that reported by Quinn et al. (2004) for ICARTT field campaign off Atlantic coast of US

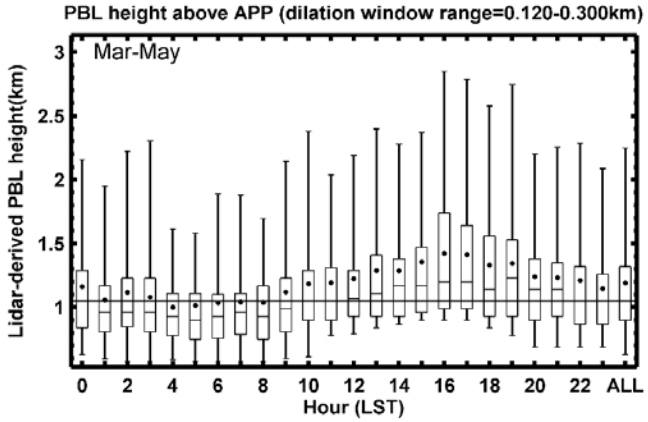
$$\gamma = -0.50\left(\frac{Org}{Org + SO4}\right) + 0.80 \quad r^2 = 0.42$$

- Measurements of hygroscopic dependence of aerosol light scattering could possibly be used to estimate organic and sulfate aerosol mass fractions (at least at this site), with similar correlation and linear model parameter to those reported off eastern US coast by Quinn et al (2005).

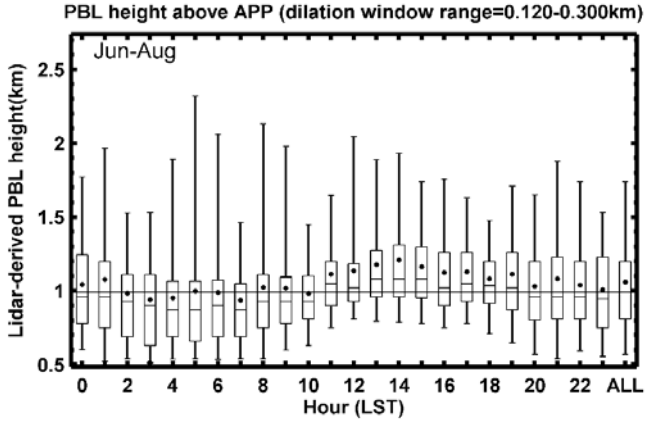
Annual and diurnal cycles of lidar-derived planetary boundary layer heights

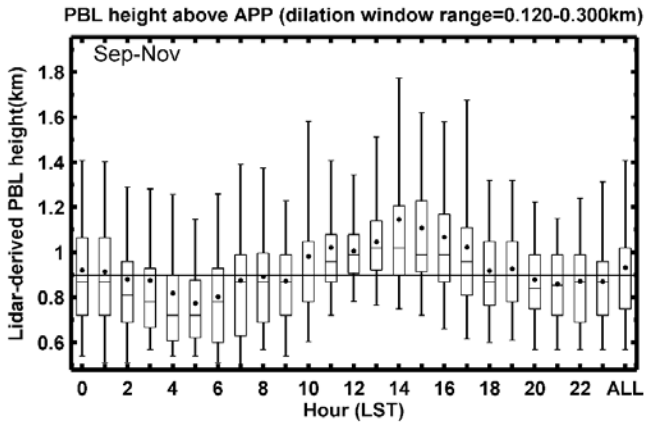




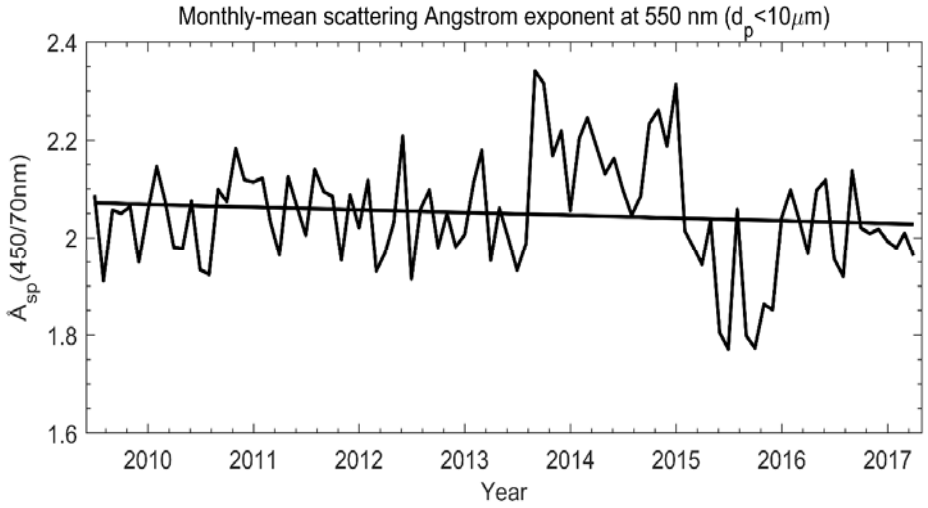


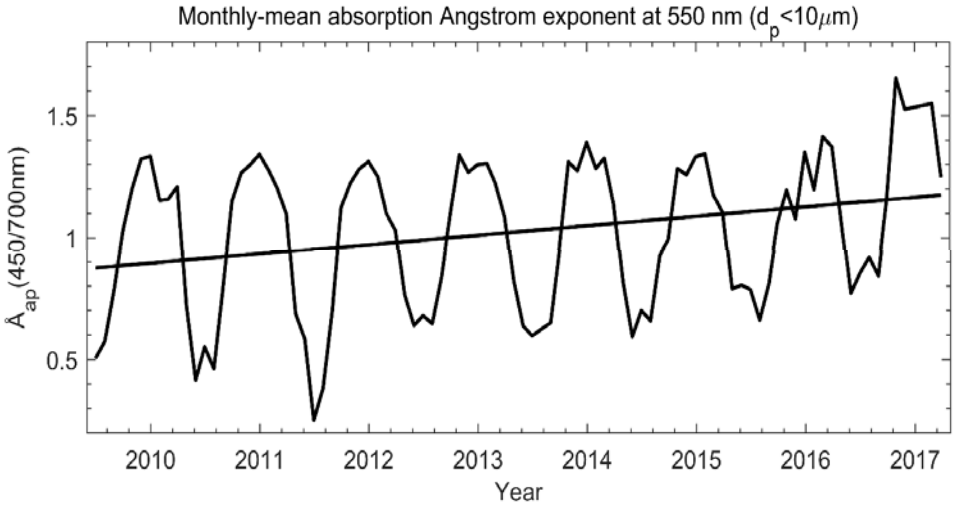
- Lidar only operational during Feb 2013-August 2014 and since March 2016 (when added to NASA MPLNET)
- PBL heights calculated using wavelet covariance transform algorithm implemented by ASU grad student Ben Madison and compared to radiosonde launches in summer 2013





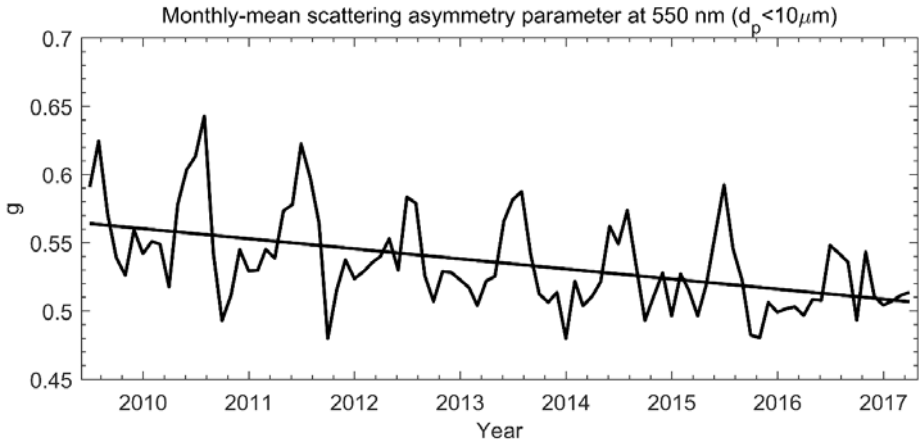
Scattering and absorption Angstrom exponents

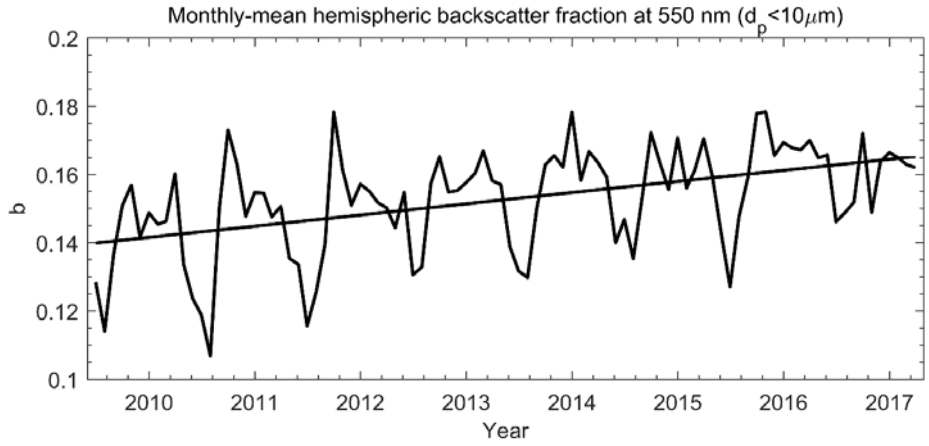




- Scattering Angstrom exponent demonstrates little long-term change (other than modulation influenced by smoke/dust events in summer 2015) and more sub-1 micron aerosol influence in 2014 (to be studied) so the fraction of scattering by sub-1 micron particles is not changing
- Absorption Angstrom exponent exhibits ‘apparent’ increase in time, possibly due to increased influence from biomass burning and (in summer) less coating of soot by transparent coatings such as sulfates and organics (Gyawali, et al. 2009)

Scattering asymmetry parameter





- Asymmetry parameter decreasing, with notable exception of June 2015 (long-distance smoke from Canadian wildfires, along with a few Saharan dust episodes
- However, scattering and absorption still dominated by sub-micron particles (next slide), indicating a shift toward smaller accumulation-mode particles (i.e. less particle growth)
- Smaller g results in more negative DRE at both the TOA and the surface (by similar amounts), as seen by the DRE sensitivity values at APP. This could (to a small degree) offset the changes in DRE due to AOD decreases