Improving Smoke and Dust $PM_{2.5}$ Analysis using Lidar Observations

Travis D. Toth (travis.d.toth@nasa.gov)[1]

Thank you for contributions from: Amy Jo Scarino[2], Marian Clayton[2], Rohit Mathur[3], Barron Henderson[3], Jim Szykman[1,3], Melanie Follette-Cook[4], and Charles Turner[5]

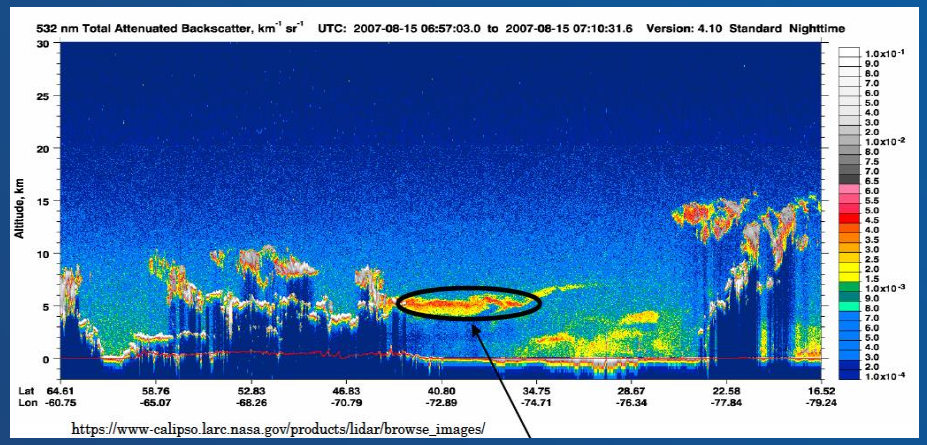
[1]NASA Langley Research Center, Hampton, VA
[2]Coherent Application, Inc. – Psionic LLC, Hampton, VA
[3]U.S. Environmental Protection Agency, Research Triangle Park, NC
[4]NASA Goddard Space Flight Center, Greenbelt, Maryland
[5]Virginia Department of Environmental Quality, Richmond, VA

Artificial Intelligence (AI) Usage Disclosure
This document was created with assistance from Microsoft Copilot for the creation of one image. The content has been reviewed and edited by Travis Toth.

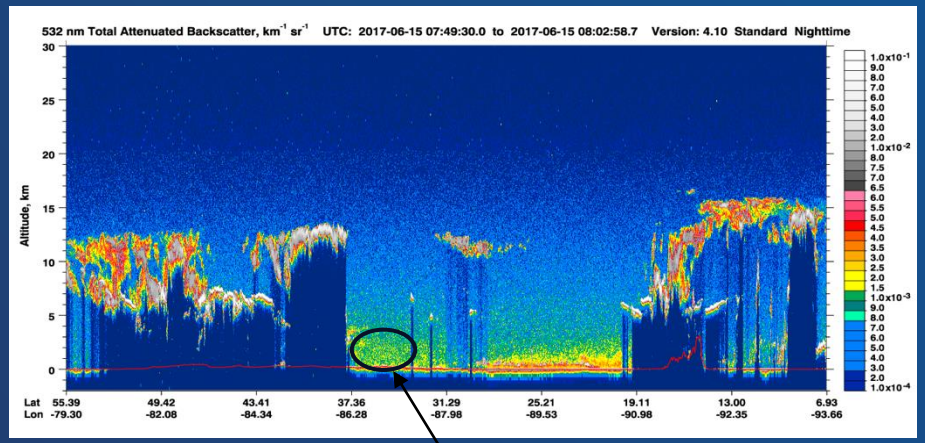
Introduction and Motivation

- Fine particulate matter ($PM_{2.5}$) is a well-known major contributor to air pollution and negatively impacts human health
- Many studies have estimated $PM_{2.5}$ concentrations from AOT from passive sensors on satellites (e.g., Terra/Aqua MODIS, GOES ABI)
- Challenge of passive approach is column-integrated perspective
- Complementary approach uses lidar: strength is vertical perspective, including near the surface
- In this talk:
  - Intro to LIDAR remote sensing
  - CALIOP-based $PM_{2.5}$ approach (Toth et al., 2019, 2022)
  - HAQAST study objectives, first results, and next steps
  - Dust Tiger Team overview

CALIPSO curtain plots:



Elevated aerosol plume

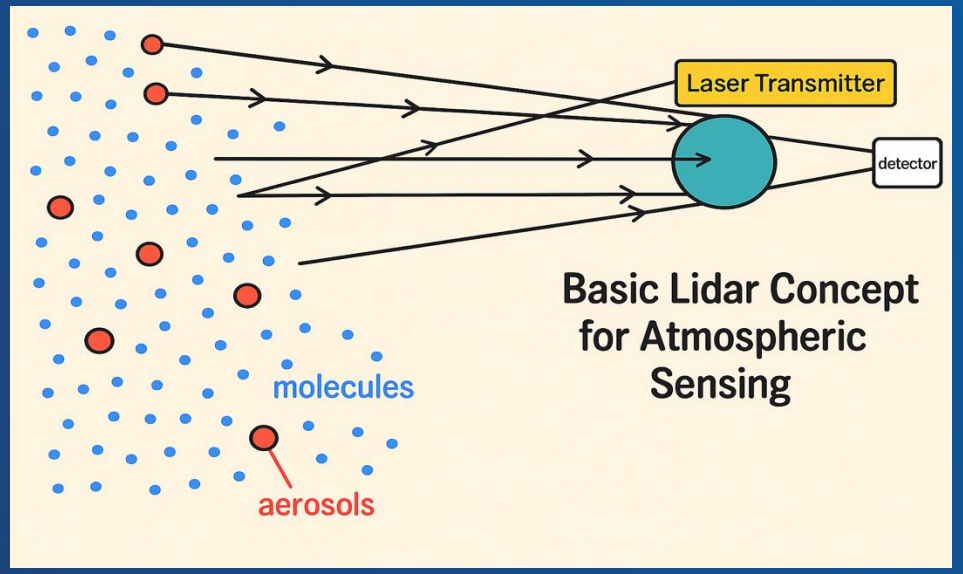


Near-surface aerosols

(https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/)

(Very!) Brief intro to LIDAR Remote Sensing and CALIPSO

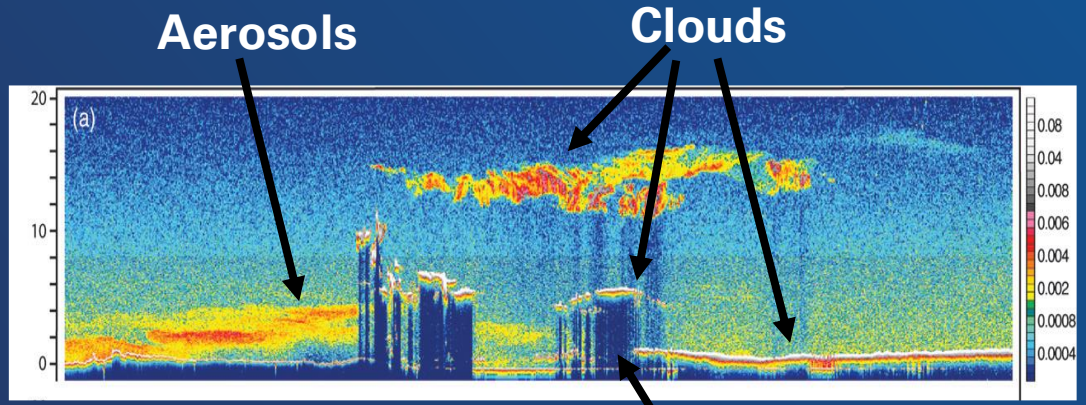
- LIDAR stands for "light detection and ranging"
- Active remote sensor (i.e., sends out a pulse of laser light)
- Airborne, ground-based, and space-based instruments
- Allows for atmospheric profiling at high vertical resolution



(Image created using generative AI; Microsoft Copilot)

Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard CALIPSO satellite

- International collaboration between U.S. (NASA) and France (CNES)
- Operations: 2006 - 2023
- Polar/sun synchronous orbit ("A-Train" satellite constellation)
- Elastic backscatter lidar (Rayleigh-Mie)
- Dual-wavelength (532 nm and 1064 nm)



(Young and Vaughan, 2009)

Estimating $PM_{2.5}$ using CALIOP (technique)

CALIOP = Cloud Aerosol Lidar with Orthogonal Polarization

- Toth et al. (2019; AMT) → described development of technique in a proof-of-concept paper & applied method over CONUS for two years (2008-2009)
- Method is based on definition of particulate matter mass concentration (extinction coefficient/mass extinction efficiency):

$$PM = \frac{\sigma}{\alpha}$$

- Additional terms to account for aerosol size distribution and aerosol hygroscopic growth

(Toth et al., 2019; Atmospheric Measurement Techniques)

Algorithm:

$$PM_{2.5} = \frac{\sigma \text{ x } \varphi \text{ x } 1000}{(\alpha_{scat} \text{ x } f_{rh} + \alpha_{abs})}$$

- α_{scat} → mass scattering efficiency (**3.40** $m^2\,g^{-1}$)
- α_{abs} → mass absorption efficiency (**0.37** $m^2\,g^{-1}$)
- φ → $PM_{2.5}$ to PM_{10} ratio (**0.60**)
- σ → extinction coefficient (m^{-1}) at 532 nm
- α → mass extinction efficiency ($m^2\,g^{-1}$)
- **$PM_{2.5}$** → $PM_{2.5}$ mass concentration ($\mu g\,m^{-3}$)
- **f_{rh}** → Hygroscopic growth factor
- **1000** → scale factor

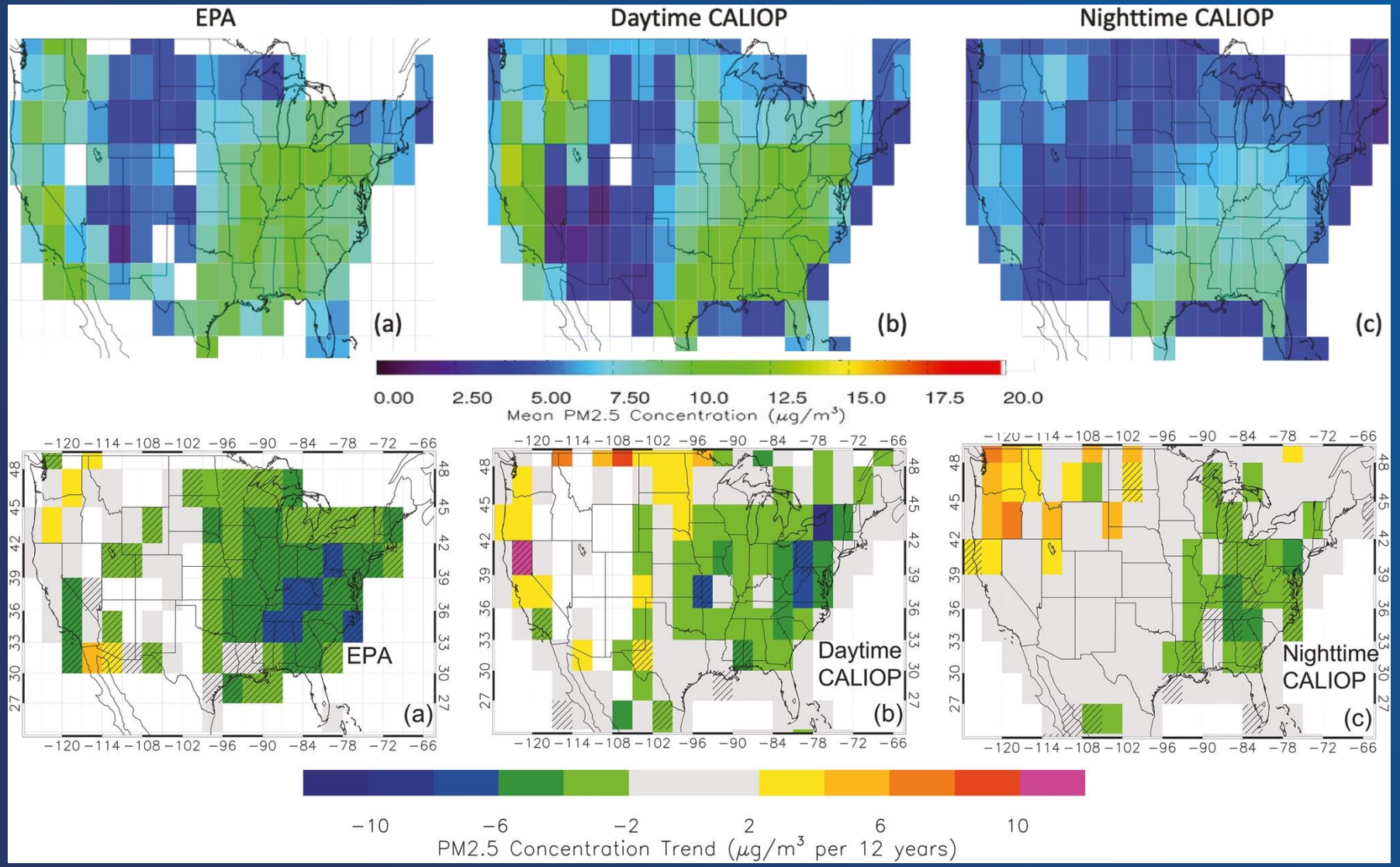
Hygroscopic growth factor:

$$f_{rh} = \left(\frac{1-RH}{1-RHref}\right)^{-\Gamma}$$

Applying lidar-based $PM_{2.5}$ technique over CONUS (2007-2018)

Mean $PM_{2.5}$ →

Trends in $PM_{2.5}$ →



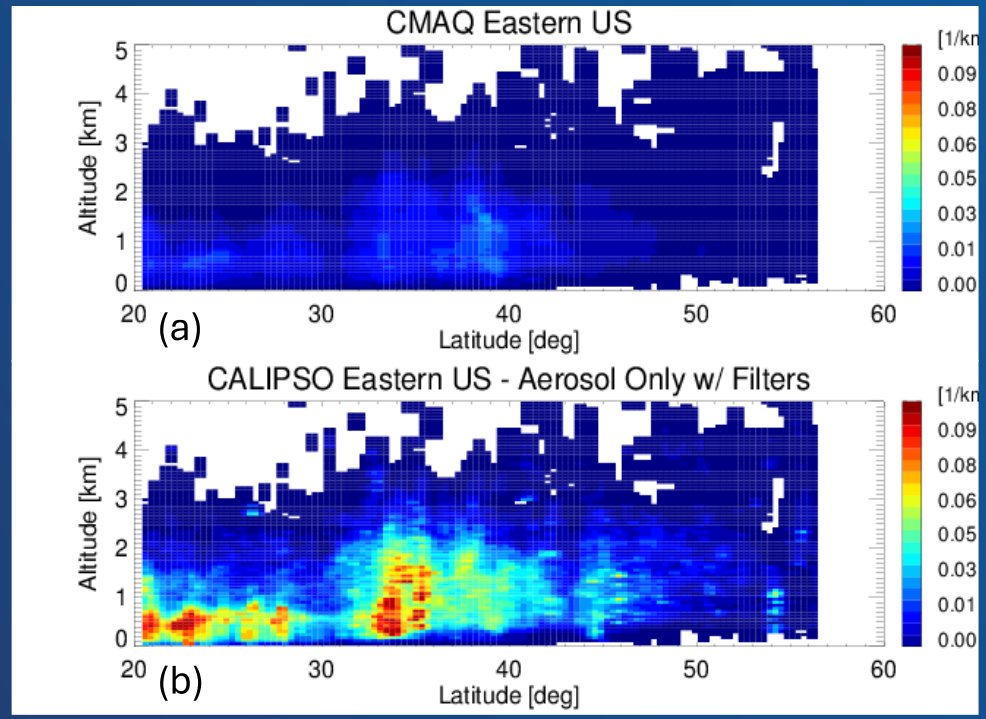
(Toth et al., 2022; Atmospheric Environment)

HAQAST project: Improving $PM_{2.5}$ Prediction and Analysis using LIDAR Observations

- Involves the study and development of fine particulate matter ($PM_{2.5}$) retrievals using lidar observations

- Objectives:
  - **Evaluate/validate aerosol extinction from air quality models (e.g., EPA's CMAQ).**
  - Develop new approaches to estimate $PM_{2.5}$ from combined model/lidar data.
  - Further develop more robust $PM_{2.5}$ estimates from a lidar-only approach.
  - Gain an understanding of the larger scale aerosol vertical distribution in the atmosphere using lidar measurements.

Monthly mean aerosol extinction for August 2010 (Eastern US; CMAQ vs. CALIOP)



Jim Szykman (EPA/LaRC)

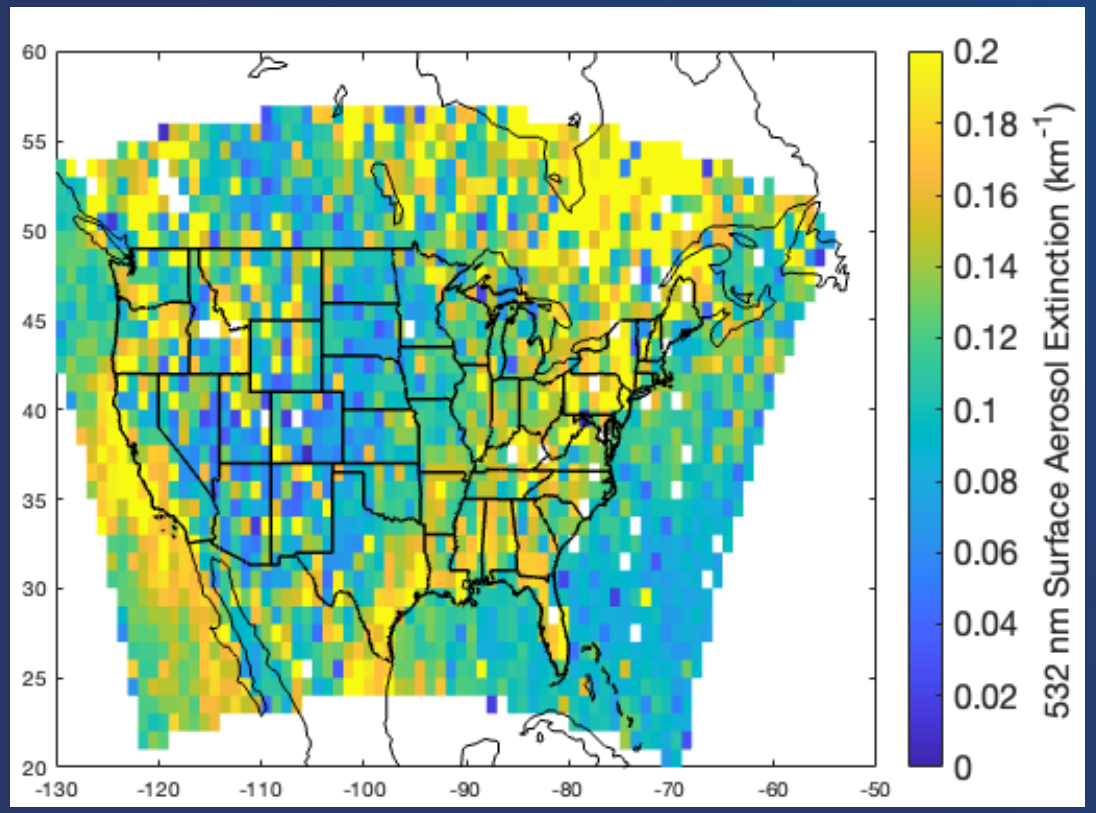
Team

NASA LaRC:
Travis Toth (PI), Amy Jo Scarino, Marian Clayton

Collaborators and end users/stakeholders:
Jim Szykman (EPA/LaRC), Melanie Follette-Cook (GSFC), Barron Henderson (EPA), Rohit Mathur (EPA), and Charles Turner and colleagues at Virginia Department of Environmental Quality (VA DEQ)

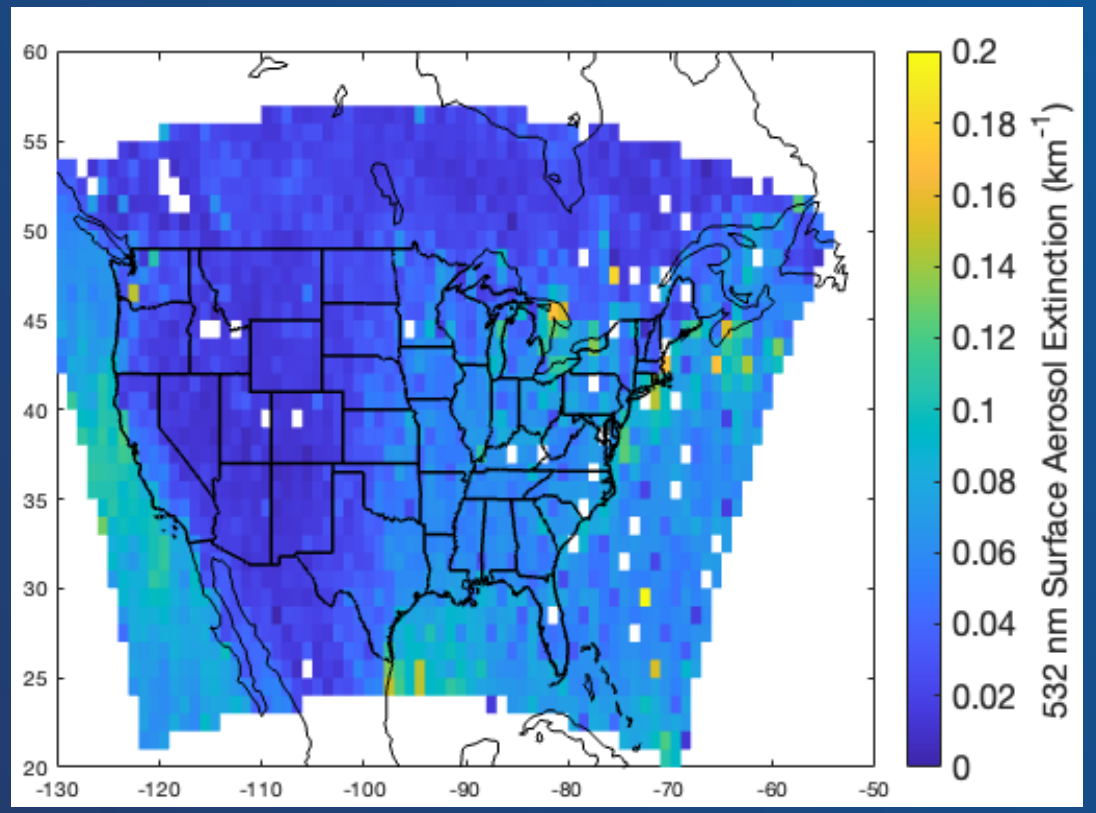
Collocated CALIOP vs. WRF-CMAQ 532 nm Surface Aerosol Extinction : Spatial Mean (2006-2019)

CALIOP



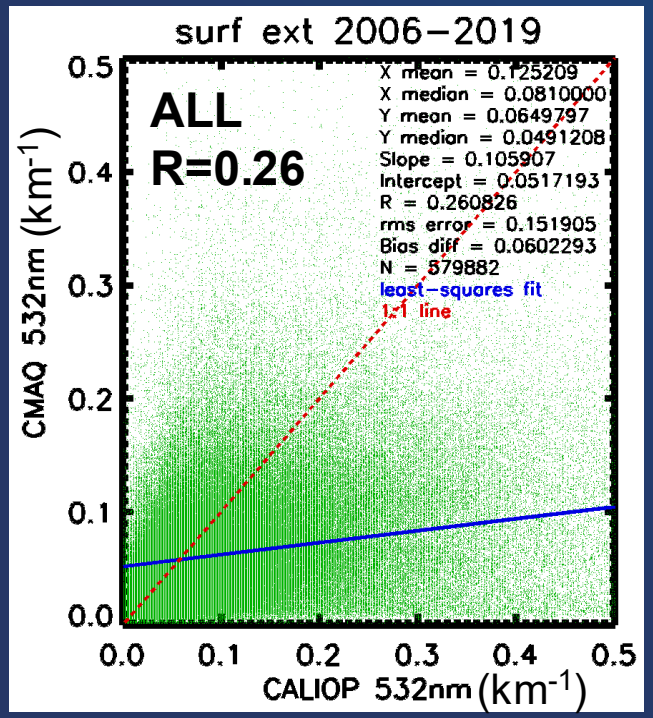
Version 5 Level 2 Aerosol Profile data; 0-120 m AGL

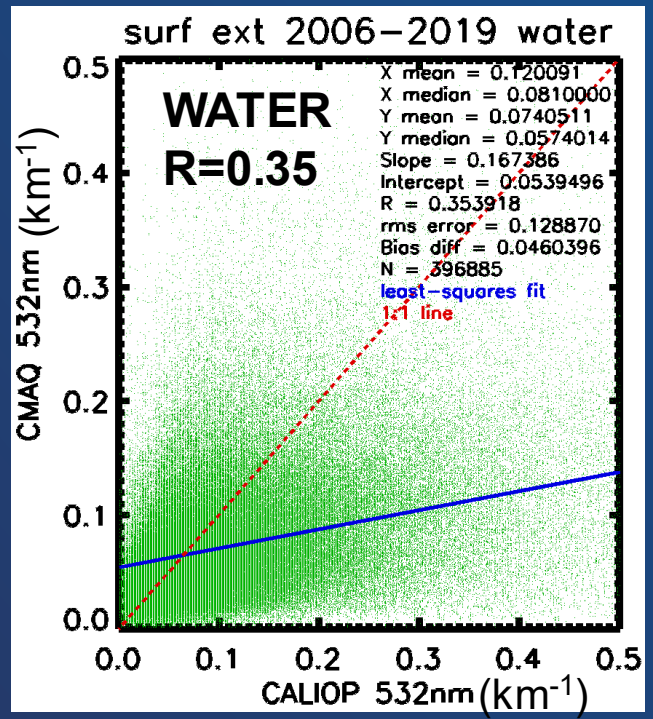
WRF-CMAQ (EQUATES)

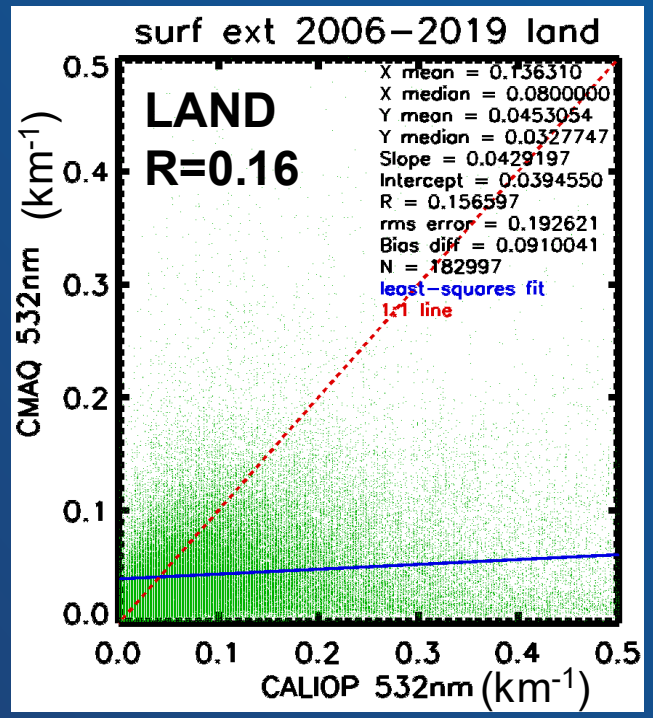


EPA EQUATES Project; PHOTDIAG3; 0-20 m AGL

CALIOP vs. WRF-CMAQ 532 nm Surface Aerosol Extinction: (2006-2019)





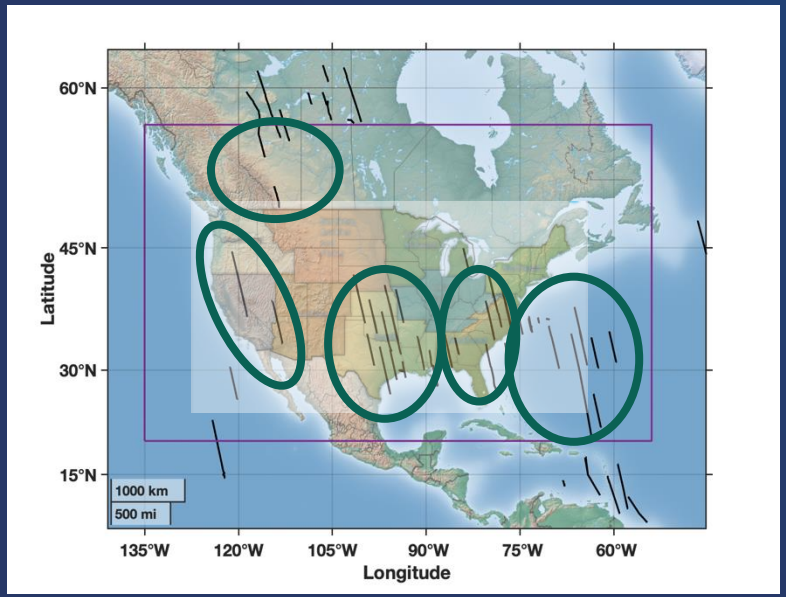


Statistics partitioned by CALIOP Aerosol Classification

CALIOP Aerosol Type	N	Slope	R	Mean Difference (km^{-1})
Marine	274,157	0.21	0.40	0.037
Dust	43,822	0.02	0.05	0.098
Polluted Continental/Smoke	74,831	0.06	0.21	0.120
Clean Continental	4,006	0.39	0.41	0.007

Current Work

- Seasonal/regional/trend analyses and case studies (e.g., wildfires)
- Airborne High Spectral Resolution Lidar (HSRL) subset studies



Western Canada
4 flights (2008)

West US region
2 flights (2016, 2017)

South US
16 flights (2006, 2007, 2009)

Southeast US
15 flights (2006-2008)

Atlantic
12 flights (2007, 2010-2011)

Summary & Using Lidars for AQ applications

- CALIOP provides historical 17-year (2006-2023) global lidar data record that can be leveraged for further air quality research
- EarthCARE's ATLID (launched May 2024) is spaceborne HSRL that can be used for current/future $PM_{2.5}$/AQ applications
- CALIOP and ATLID will be used for wildfire/prescribed fire studies, dust plume applications, and exceptional event demonstrations of lidar profiles for AQ managers (HAQAST tiger team activities)
- CALIOP and ATLID can demonstrate $PM_{2.5}$ applications in preparation for future spaceborne lidars (e.g., NASA's FALCON missions)

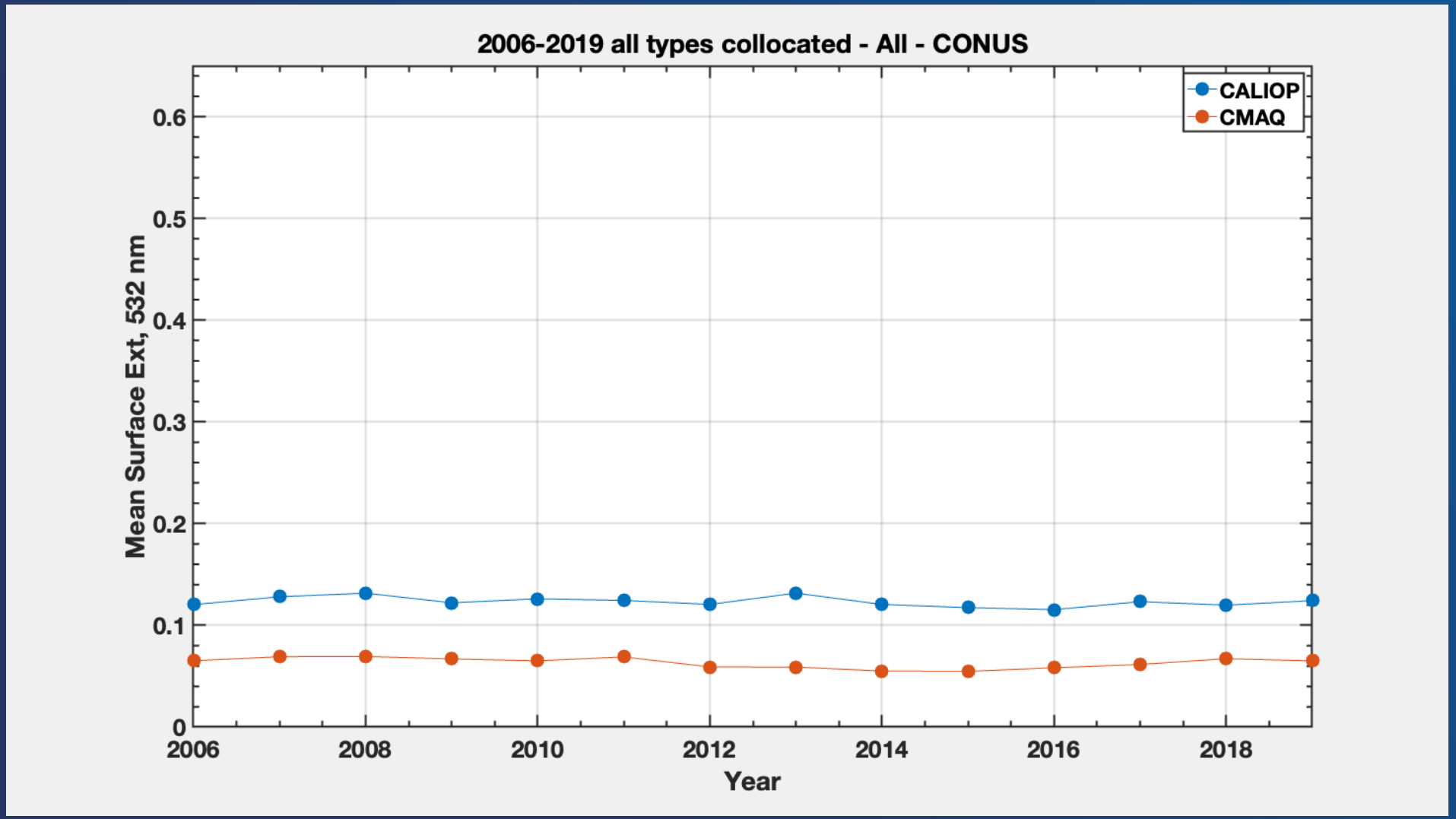
Tiger Team: *Using NASA Observations to Characterize Dust Plume Transport for Air Quality and Public Health Solutions*

- HAQAST Team: Toth, Chen, Pierce, Holloway, Reddy, Malings, King, Mao, Bellamy, Gupta, Martin, and Schlosser
- Current End User/Stakeholder Organizations: South Coast Air Quality Management District, New Mexico Department of Health, Maricopa County Air Quality Department, and George Mason University/World Meteorological Organization
- Initial Focus Regions: Southern CA, AZ, NM, AK
- Some examples of needs to be addressed: Regulatory extreme dust event demonstrations, vertical occurrence of dust below/above the boundary layer (for model evaluation), dust transport patterns and climatology, dust $PM_{2.5}$ and PM_{10}

*****We're seeking additional end users! If interested, please contact me at: travis.d.toth@nasa.gov*****

BACKUP SLIDES

Temporal – CONUS – All Aerosol Subtypes

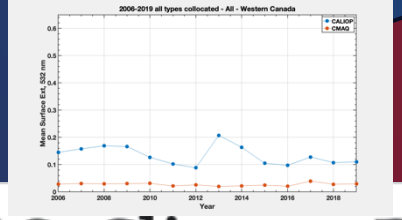


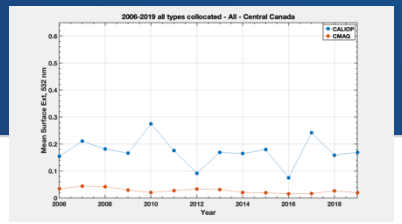
U.S. Climate Regions

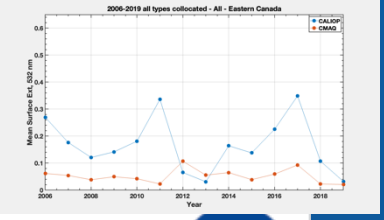
Western Canada

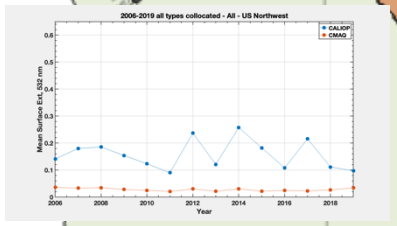
Central Canada

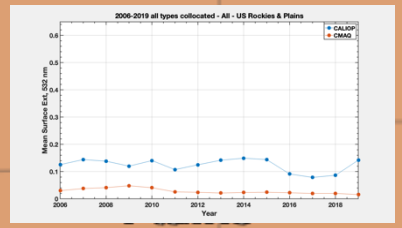
Eastern Canada

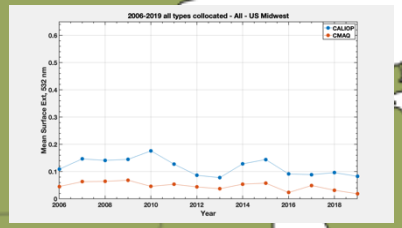


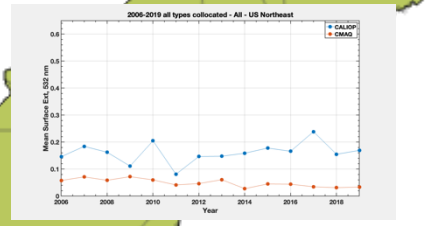


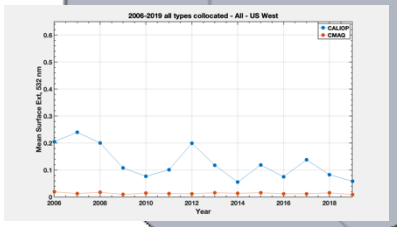


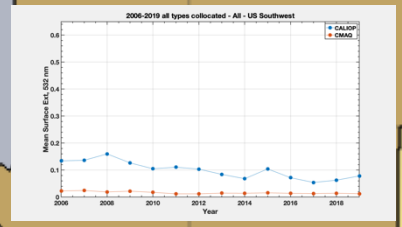


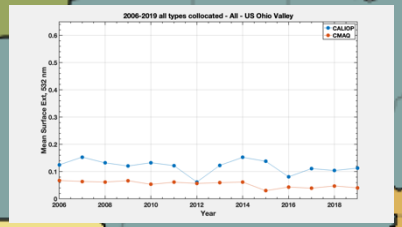


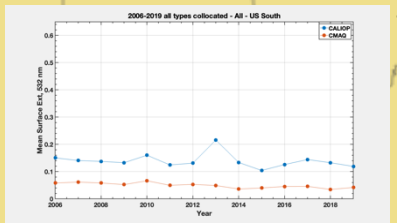


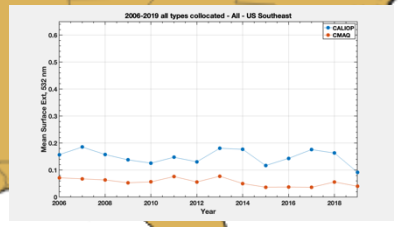






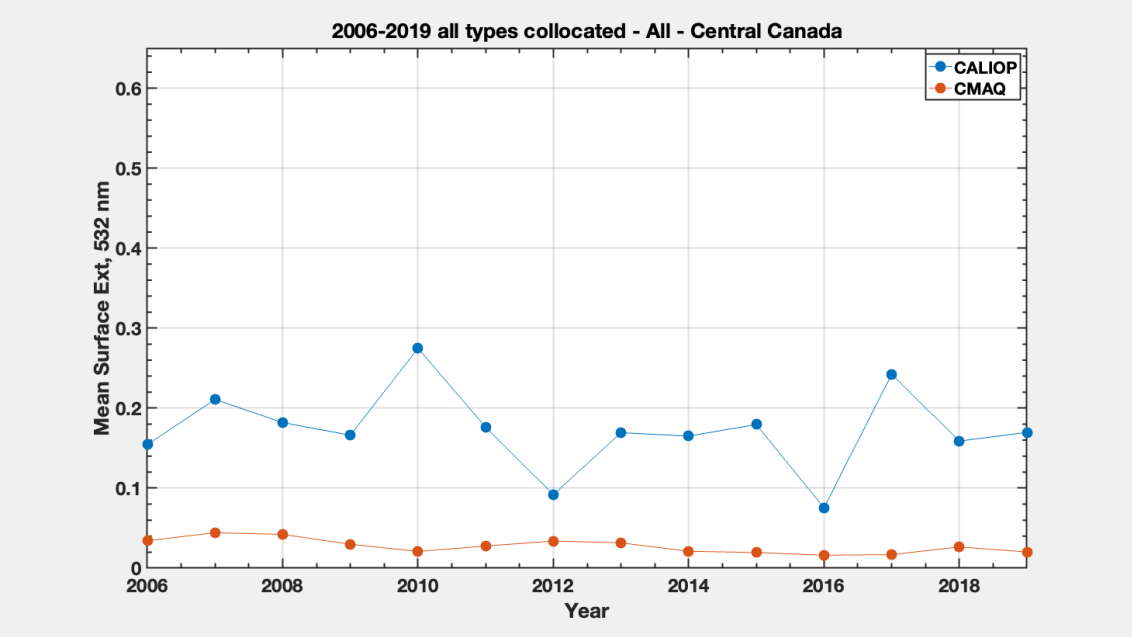




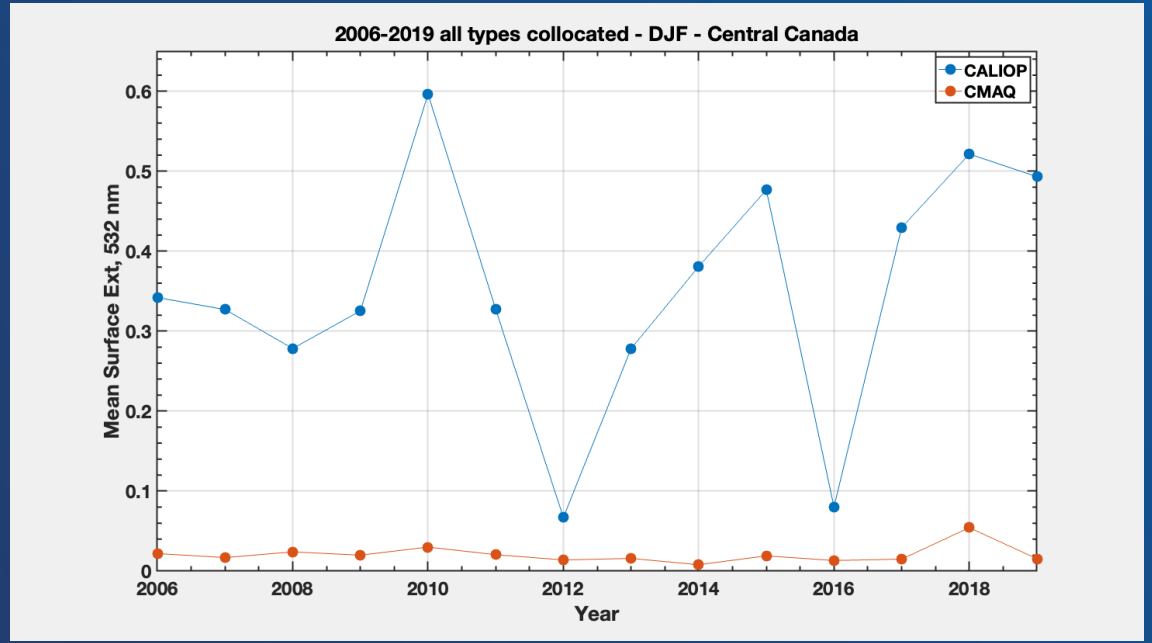


Central Canada – Ontario and Quebec

2006-2019 (All Months)



2006-2019 (DJF)



CALIOP/WRF-CMAQ aerosol extinction comparisons over CONUS (*Data & Methods*)

1. Process CALIPSO data and produce QAed surface aerosol extinction datasets over CONUS and Northern Hemisphere (*Version 5 Level 2 Aerosol Profile data; 0-120 m AGL*)
2. Ångström-interpolate WRF-CMAQ surface aerosol extinction from 381 nm and 607 nm to CALIOP's wavelength (532 nm) (*EPA EQUATES Project; PHOTDIAG3; 0-20 m AGL*)
3. Perform spatial (12 km) and temporal (1 hour) collocation of CALIOP and WRF-CMAQ over study period (2006-2019).
4. Conduct CMAQ/CALIOP comparisons for all available collocations and subsequently partition by surface type and CALIOP aerosol classification.
5. Perform initial temporal analyses (e.g., yearly, monthly, seasonally).

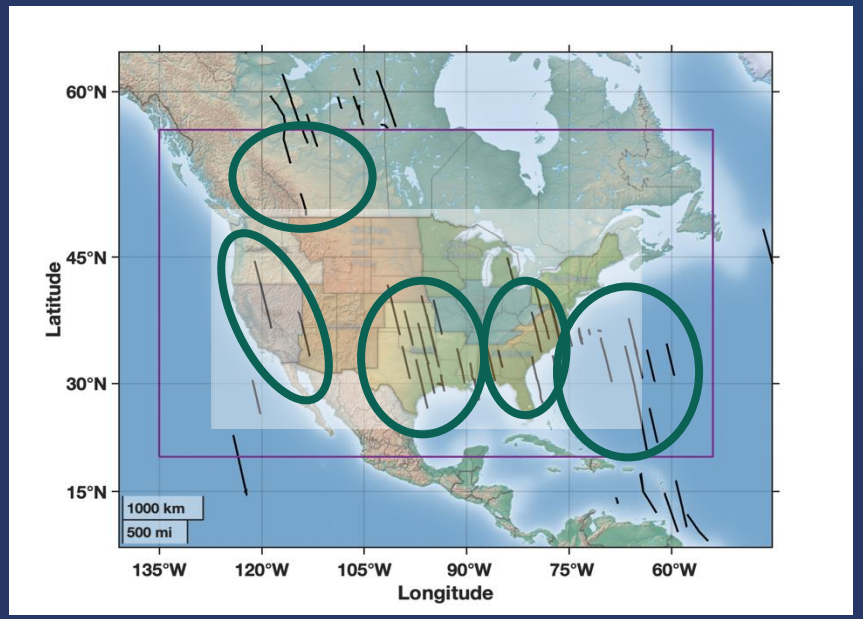
Statistics for All CALIOP Aerosol Types

CALIOP Aerosol Type	N	Slope	R	Mean Diff.
Marine	274,157	0.21	0.40	0.037
Dusty Marine	93,663	0.14	0.33	0.051
Dust	43,822	0.02	0.05	0.098
Polluted Dust	80,218	0.05	0.15	0.067
Polluted Continental/Smoke	74,831	0.06	0.21	0.120
Elevated Smoke	9,185	0.07	0.27	0.157
Clean Continental	4,006	0.39	0.41	0.007

Current Work & Next Steps

*Near-term:

- Seasonal/regional/trend analyses and case studies (e.g., wildfires)
- Comparisons with Level 3 CALIPSO aerosol product (gridded, monthly)
- Airborne High Spectral Resolution Lidar (HSRL) subset studies ⬇



West US region
2 flights (2016, 2017)

Western Canada
4 flights (2008)

South US
16 flights (2006, 2007, 2009)

Southeast US
15 flights (2006-2008)

Atlantic
12 flights (2007, 2010-2011)

*Longer-term:

- Lidar-derived $PM_{2.5}$ estimates (further development of algorithm)
- Analysis of EPA EQUATES $PM_{2.5}$ concentrations and comparisons with lidar $PM_{2.5}$ retrievals
- Aerosol vertical distribution studies (WRF-CMAQ vs. CALIOP), including surface-to-column aerosol representativeness: model vs. observations

Summary, looking ahead, and other AQ applications using lidars

- CALIPSO/CALIOP provided a 17-year (2006-2023) global lidar data record that can be leveraged for further air quality research (e.g., application of different $PM_{2.5}$ approaches to various regions, $PM_{2.5}$ trends, comparisons with models, etc.)
- EarthCARE's ATLID (launched May 2024) is a spaceborne High Spectral Resolution Lidar (HSRL) that can be used to develop $PM_{2.5}$ algorithms, perform case studies, and help extend lidar record of CALIPSO
- CALIPSO's lidar record (historical) and ATLID (current) will be used for wildfire/prescribed fire studies, dust plume applications, and exceptional event demonstrations of lidar profiles for AQ managers (HAQAST tiger team activities)
- Measurements/retrievals from both CALIOP and ATLID can demonstrate $PM_{2.5}$ techniques in preparation for future spaceborne lidars (e.g., NASA's FALCON and ASI's Luce mission)