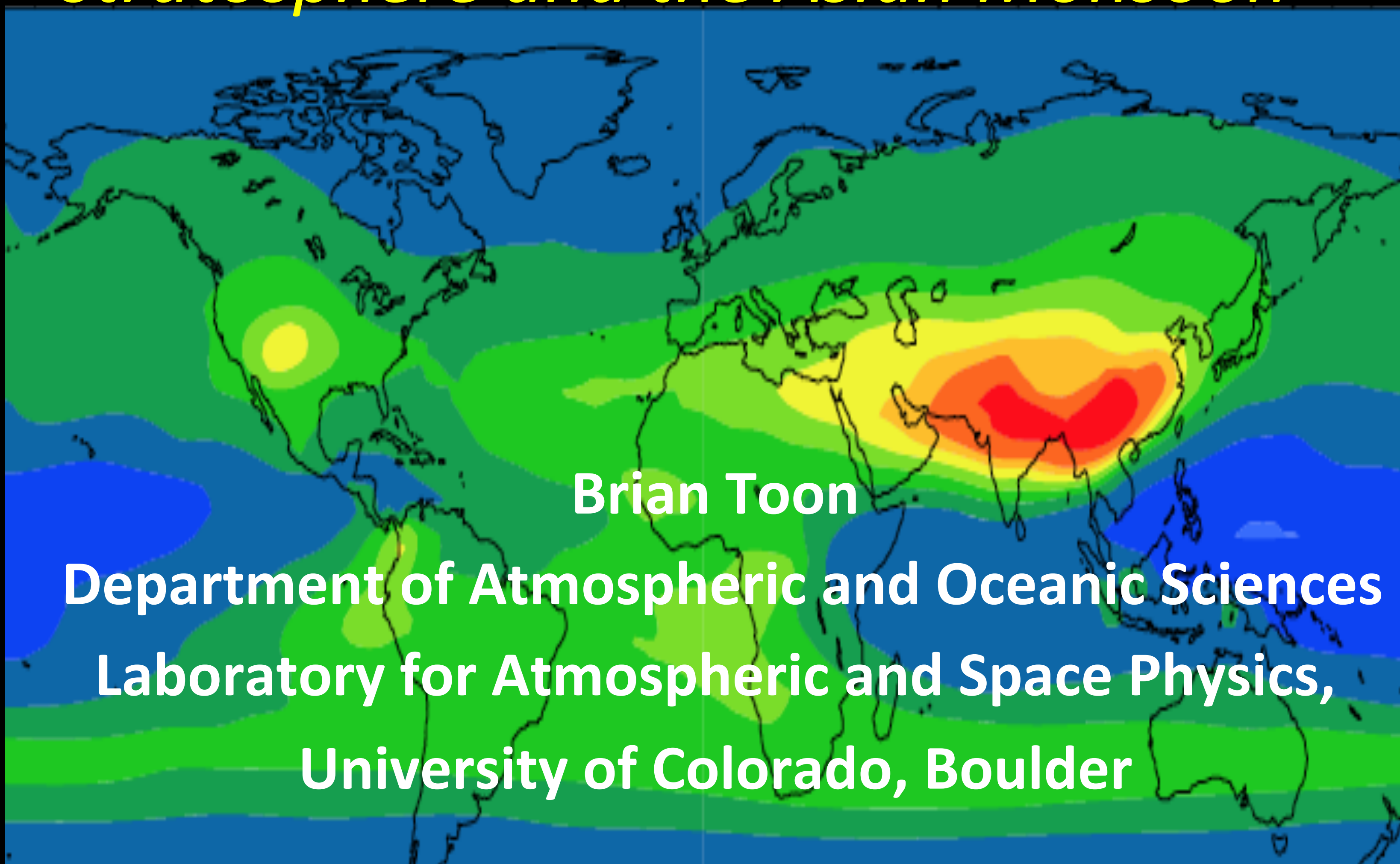
# *Aerosols in the upper troposphere and lower stratosphere and the Asian Monsoon*



**Brian Toon**

**Department of Atmospheric and Oceanic Sciences**

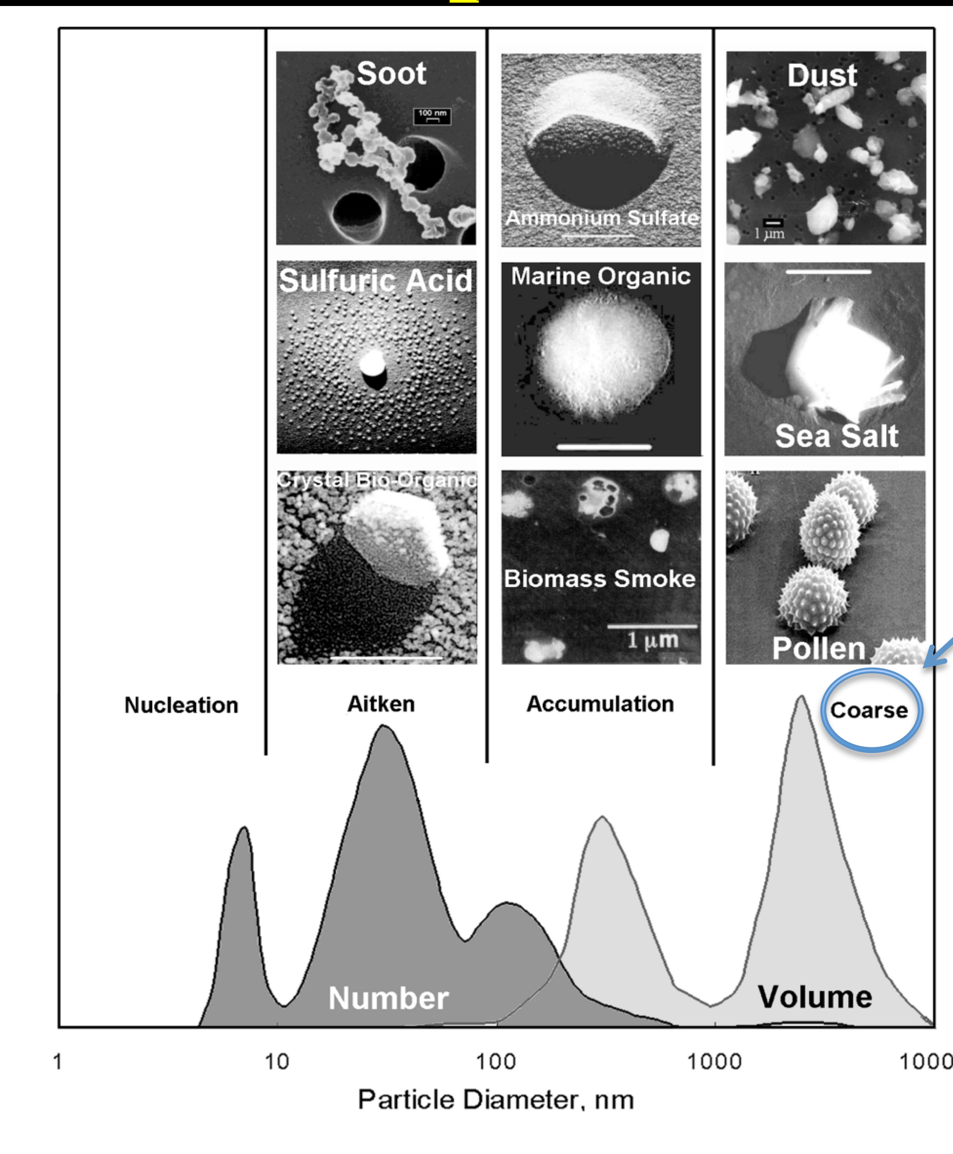
**Laboratory for Atmospheric and Space Physics,**

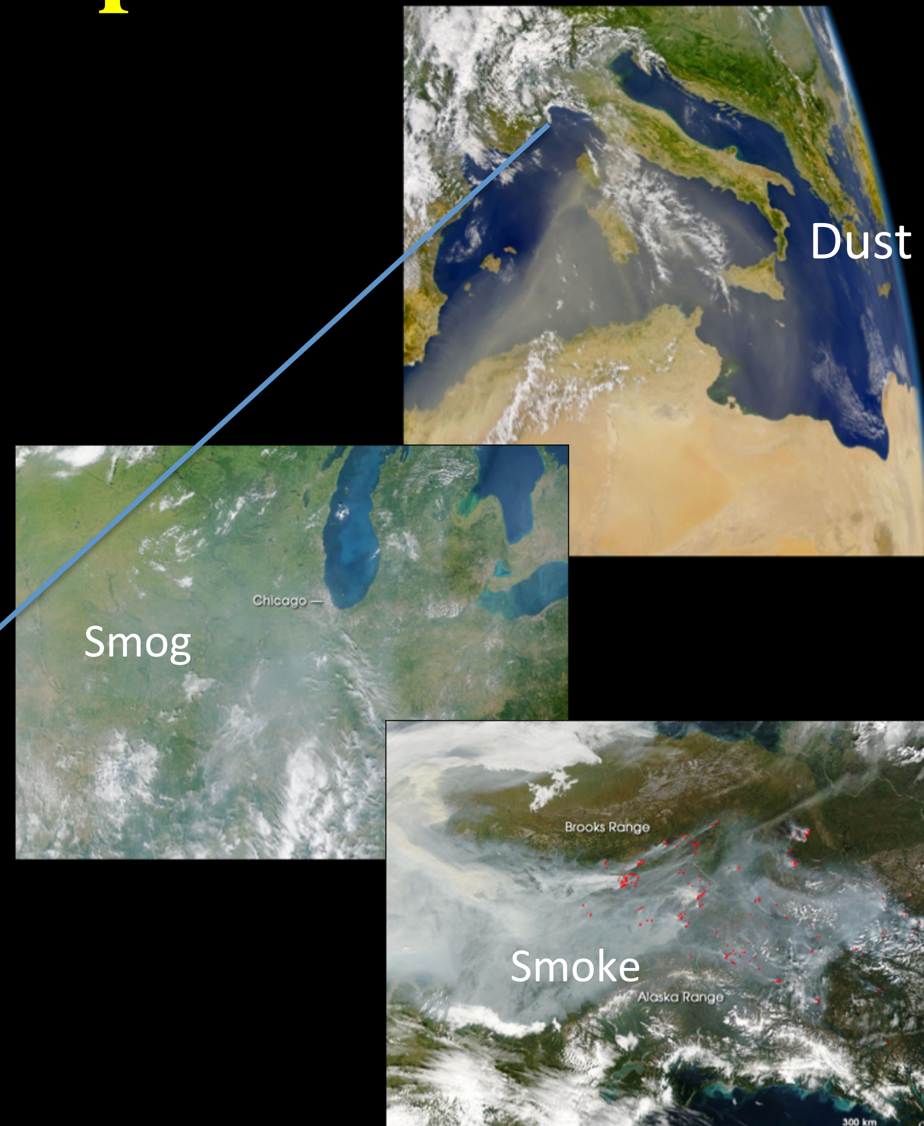
**University of Colorado, Boulder**

ATOC

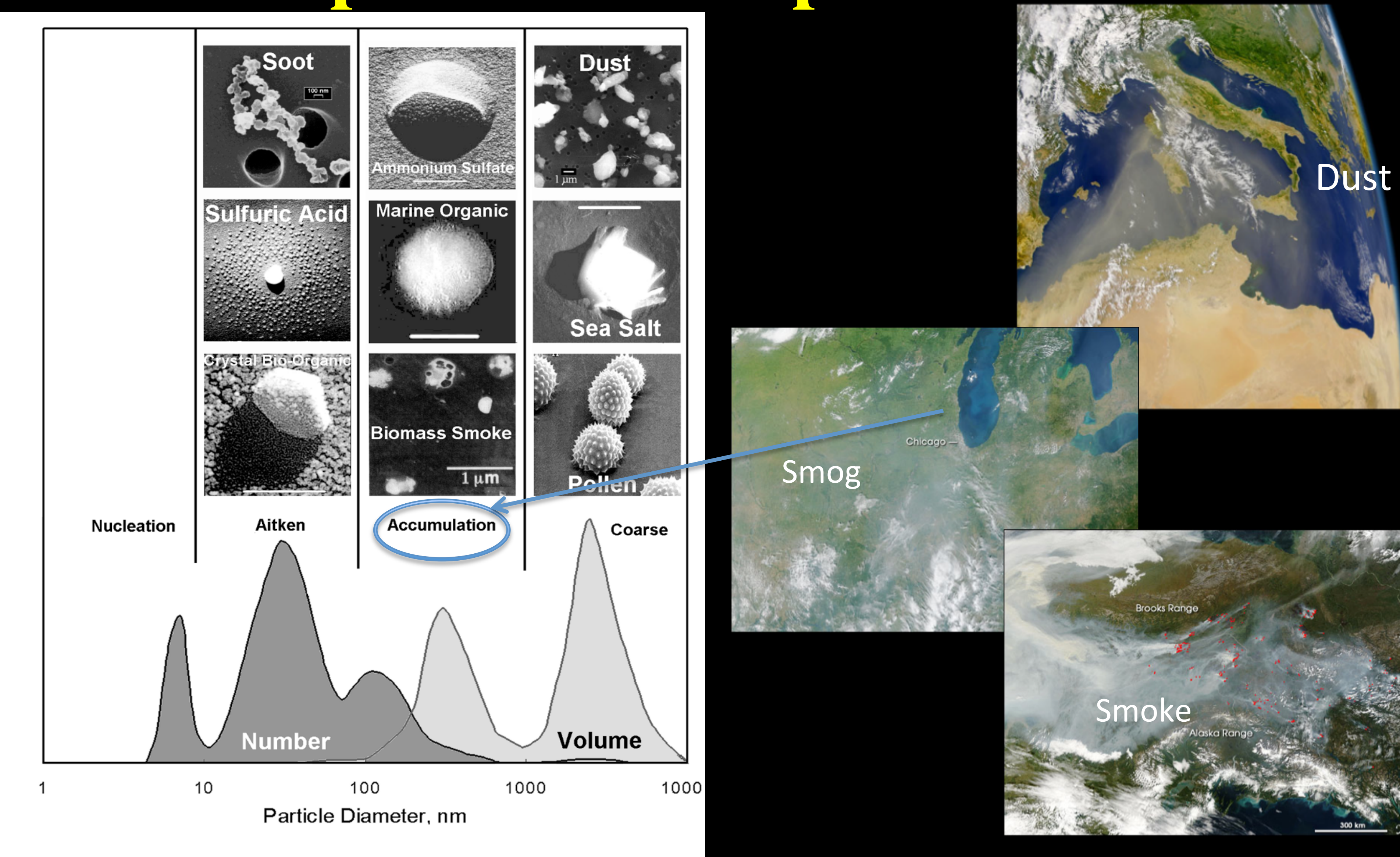
# An aerosol is a suspension of particles in a gas

# Aerosols have a range of compositions and particle sizes

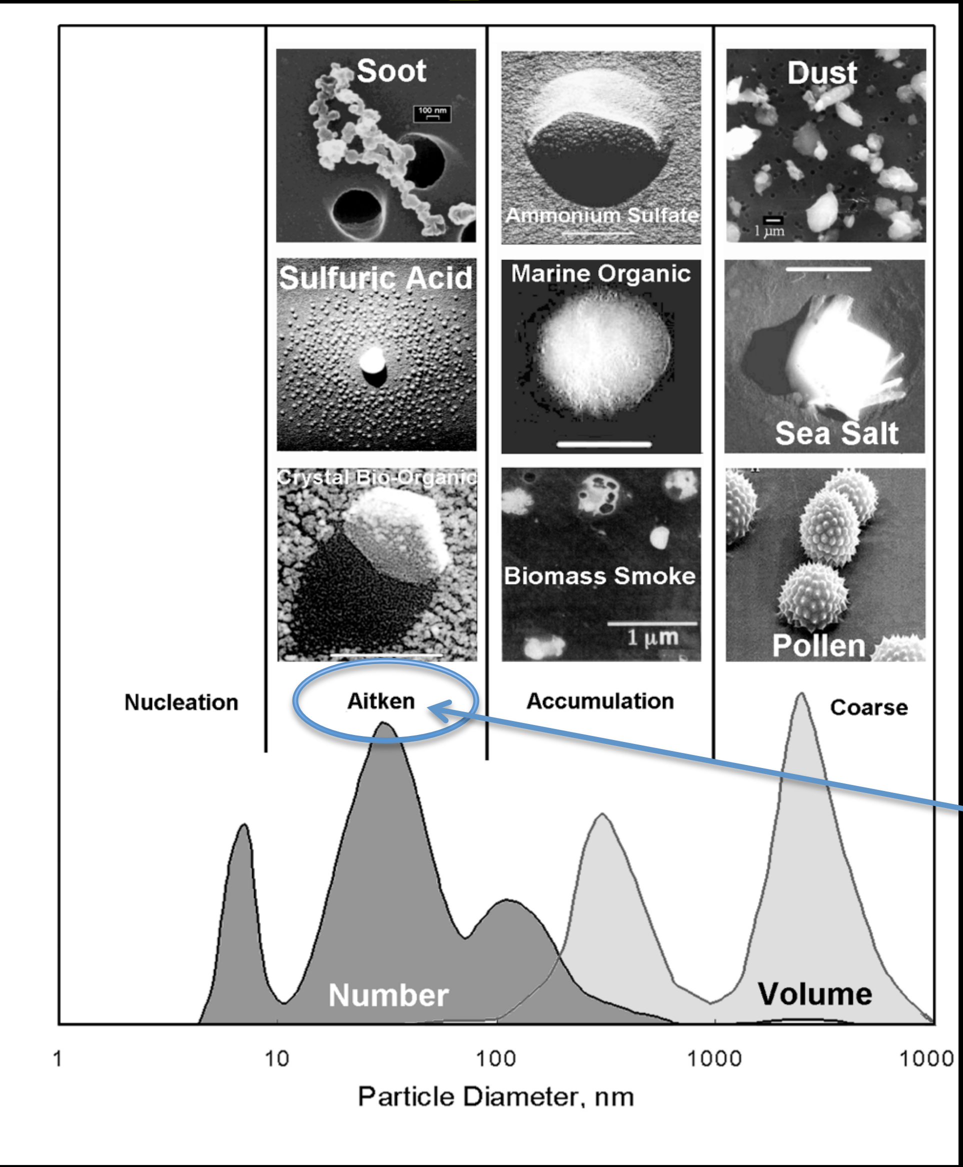


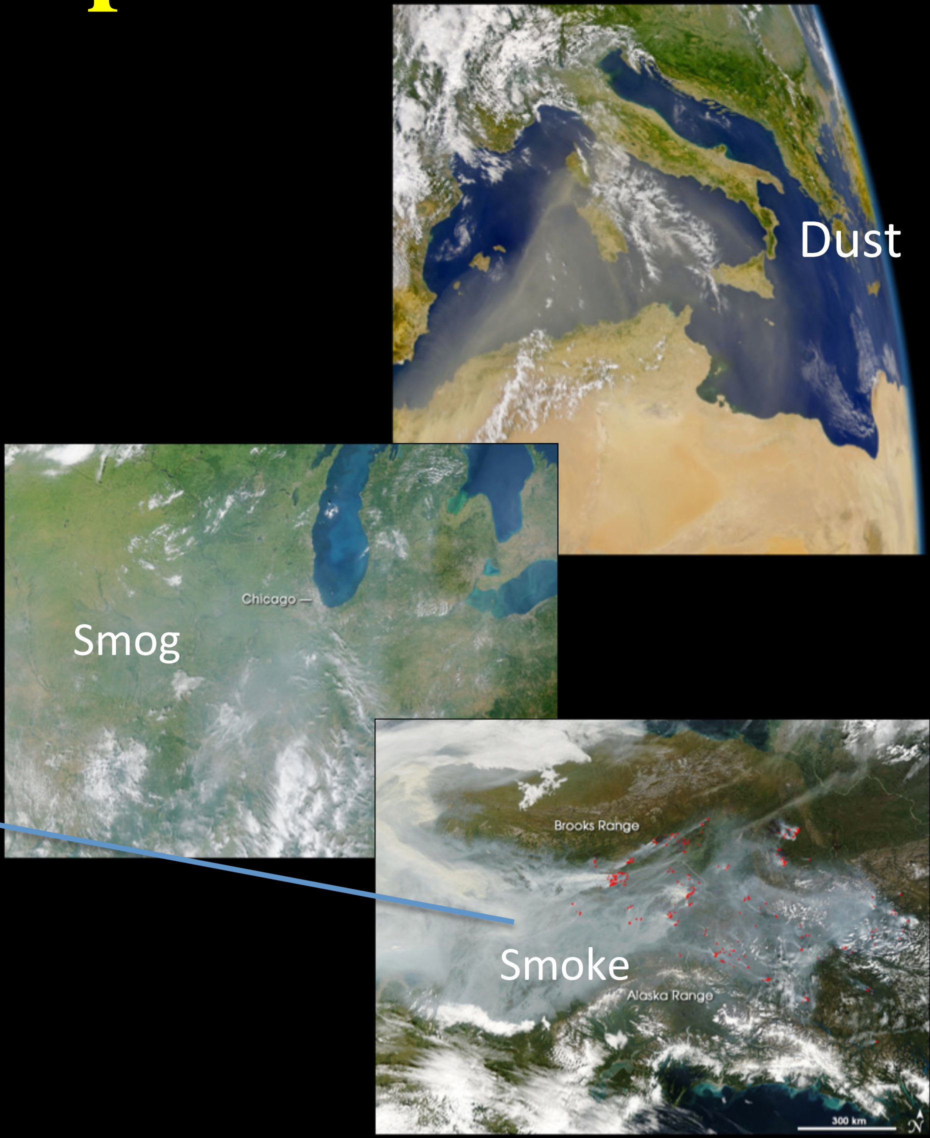



# Aerosols have a range of compositions and particle sizes

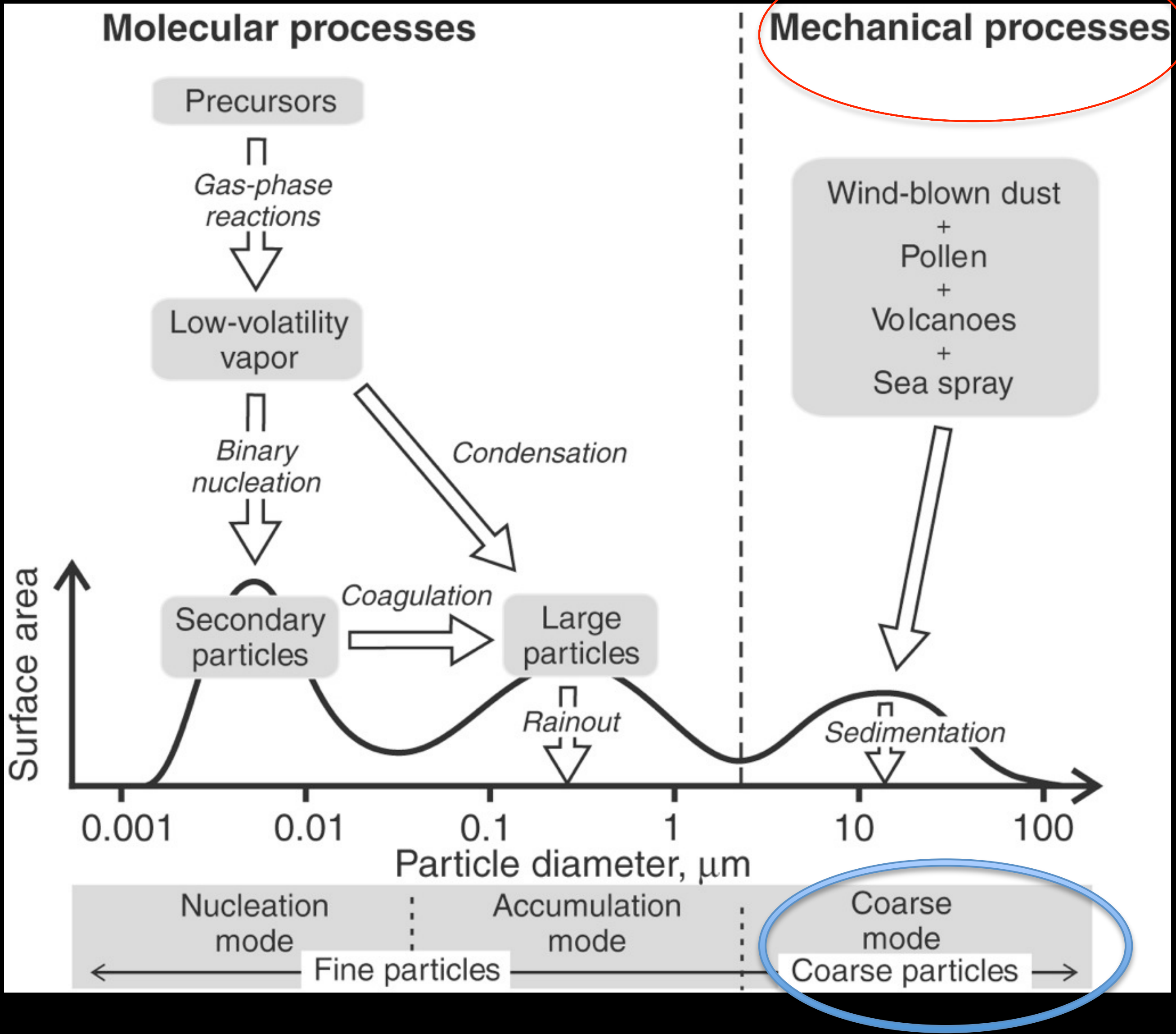


# Aerosols have a range of compositions and particle sizes

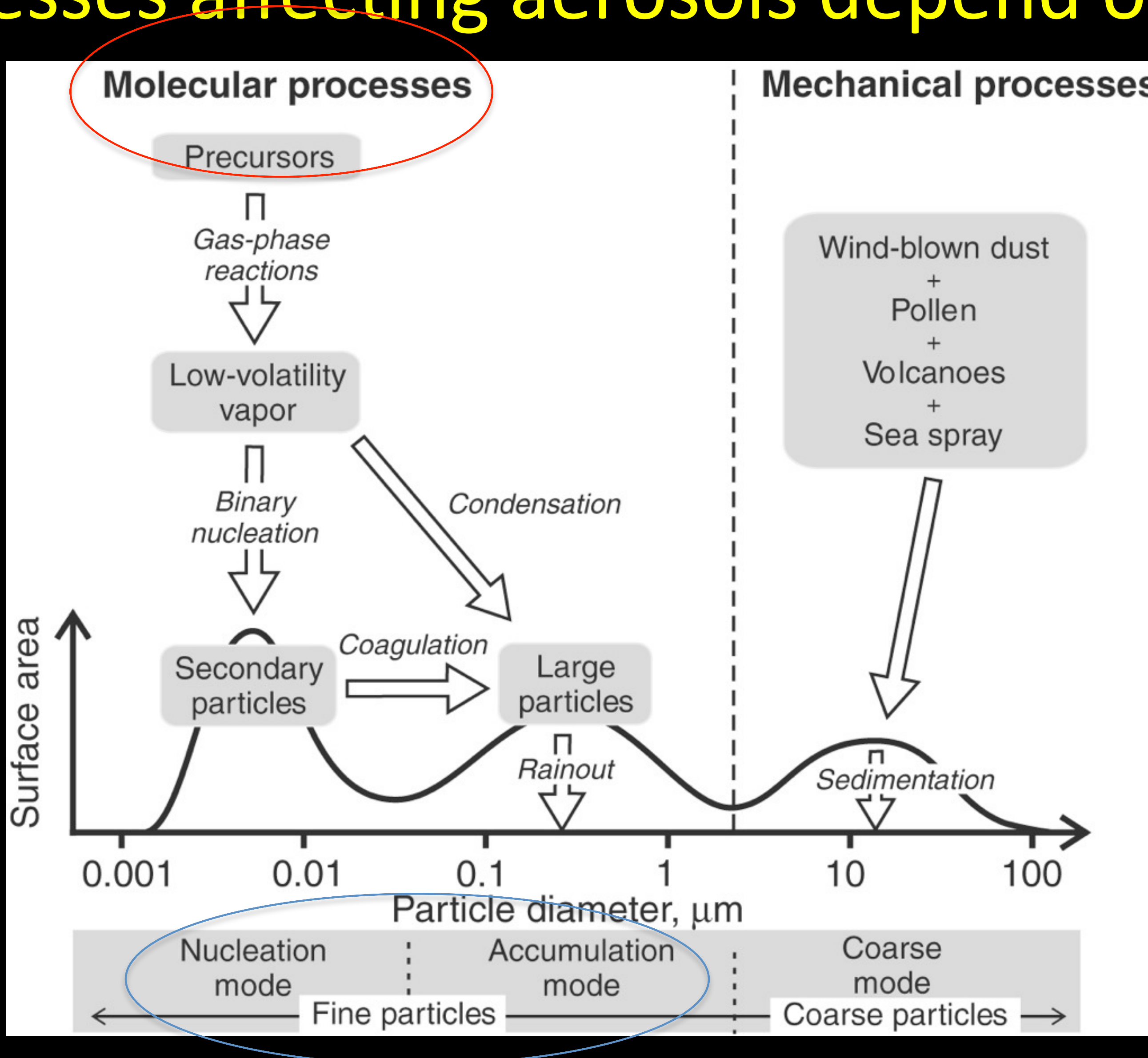


# Processes affecting aerosols depend on size



# Processes affecting aerosols depend on size



# Due to wide range of particle sizes, computer models have trouble simulating clouds and aerosols

| | |
|---|---|
| Number of meteorological variables | 10 |
| Number of gases | 100 |
| Number of aerosol and hydrometeor distributions | 5 |
| Number of size bins per distribution | 20 |
| Number of components per size bin per distribution | 30 |
| Number of radiative variables: | 2 |
| Number of three-dimensional grid cells | 50,000 |
| Number of surface variables | 6 |
| Number of two-dimensional grid cells | 2500 |
| → Number of array points required | 156 million |

Jacobson, Atmospheric modeling

# What do we do to limit storage/run times?

- Bulk aerosol models, only include mass = GEOS 5, NRL, CESM old aerosol and cloud models. Dr. Mian Chin
- Two moment models, include mass & number = CESM-Morrison and Gettelman cloud models.
- Modal Models, assume particle size modes = CESM modal aerosol models. Professor Xiaohong Liu
- Sectional or Size Resolved Models = CESM CARMA aerosol and cirrus models. Professor Brian Toon

# CARMA -4 decades of development

- Sulfate: Rich Turco, Pat Hamill, Mike Mills, Jason English, C. S. Kiang
- Dust: Doug Westphal, Peter Colarco, Lin Su
- Sea Salt: Tianyi Fan, Lansing Madry
- Smoke: Jamison Smith, Rebecca Matichuk
- BC & OC: Pengfei Yu
- Polar Stratospheric Clouds: Yunqian Zhu
- PMC, Meteor Smoke: Rich Turco, Charles Bardeen, Ryan Neely
- Ice and Water Clouds : Andy Ackerman, Eric Jensen, Charles Bardeen, J. Smith, Lu Wang, Chris Maloney

- Interface to CESM: Charles Bardeen
- Coupled Aerosol Package: Pengfei Yu

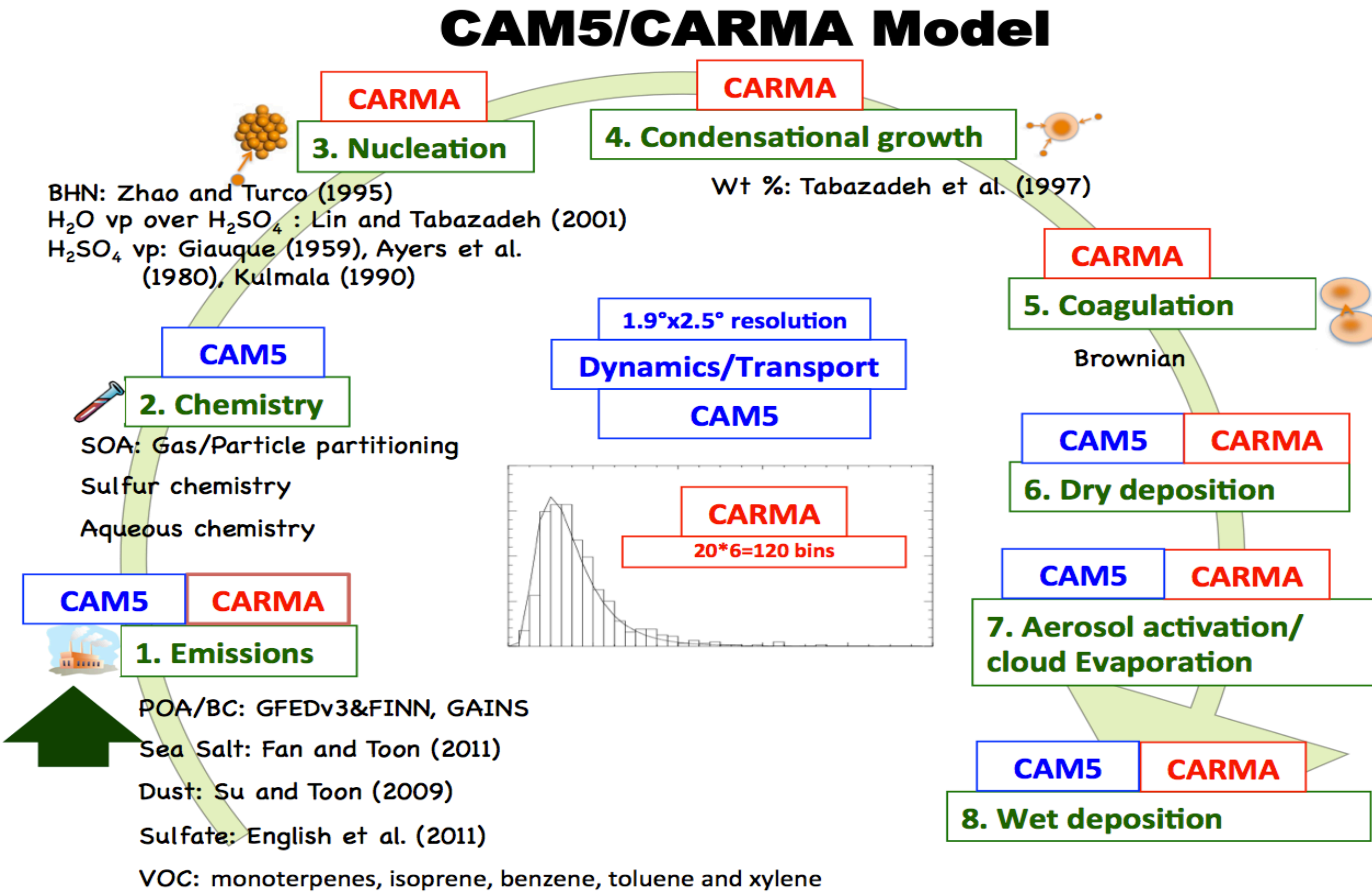
# CARMA also used for:

- Venus
- Mars
- Titan
- Pluto
- Early Earth

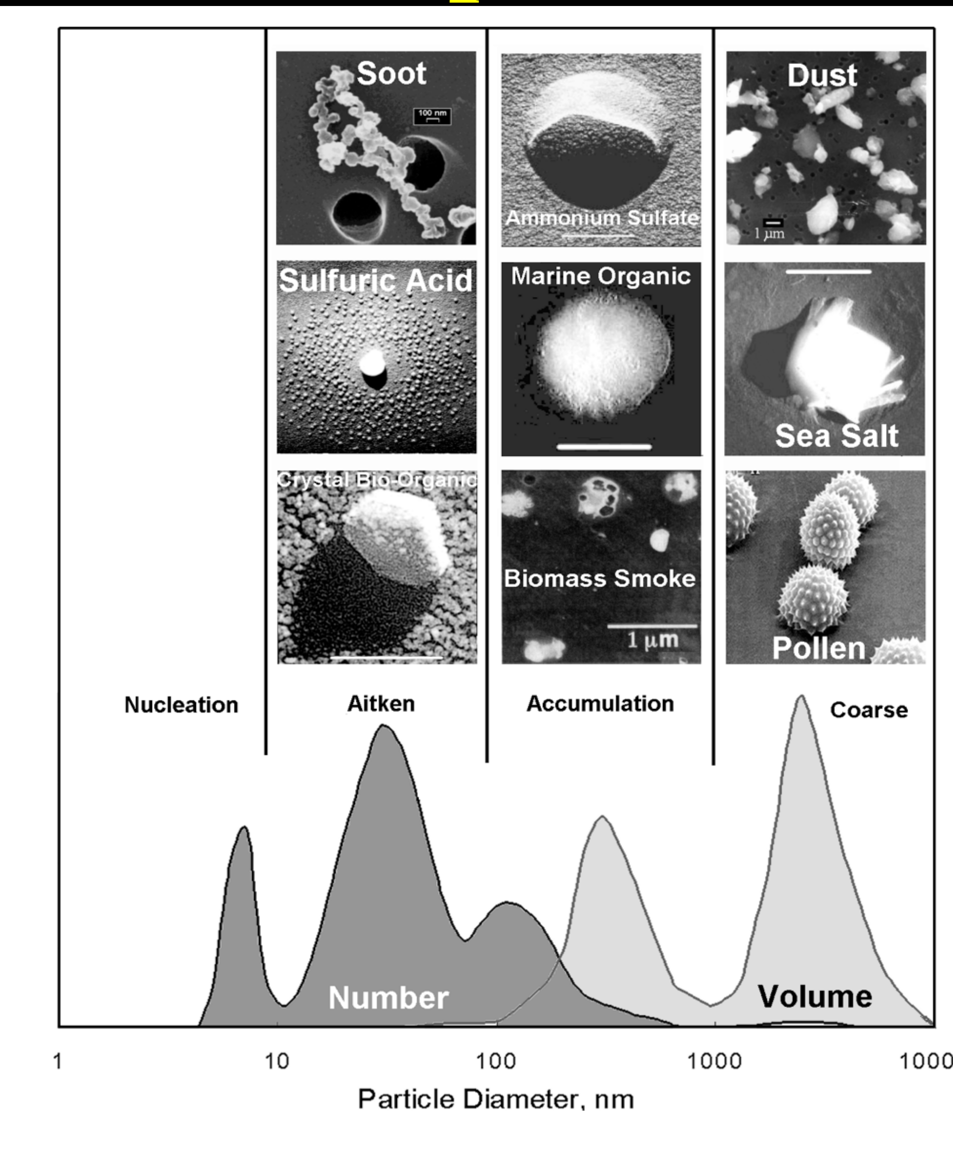
# Today I will describe work by Pengfei Yu

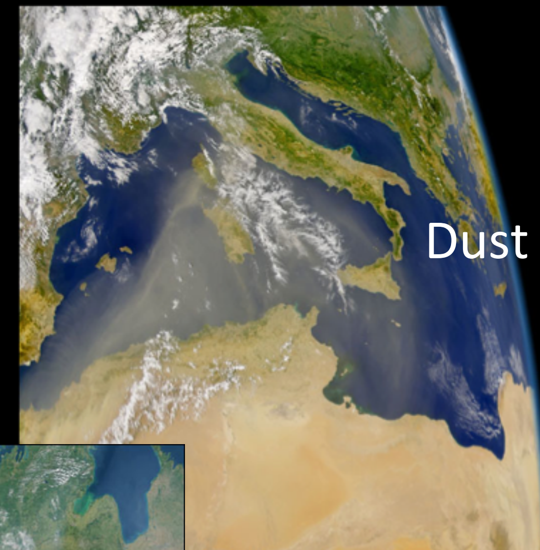

- PhD from CU-Boulder, in Brian Toon's group
- Develop aerosol package: CESM/CARMA
- Now Postdoc at NOAA CSD (Karen Rosenlof)

# CARMA is a Sectional Aerosol Microphysics model coupled with CESM (CAM5)



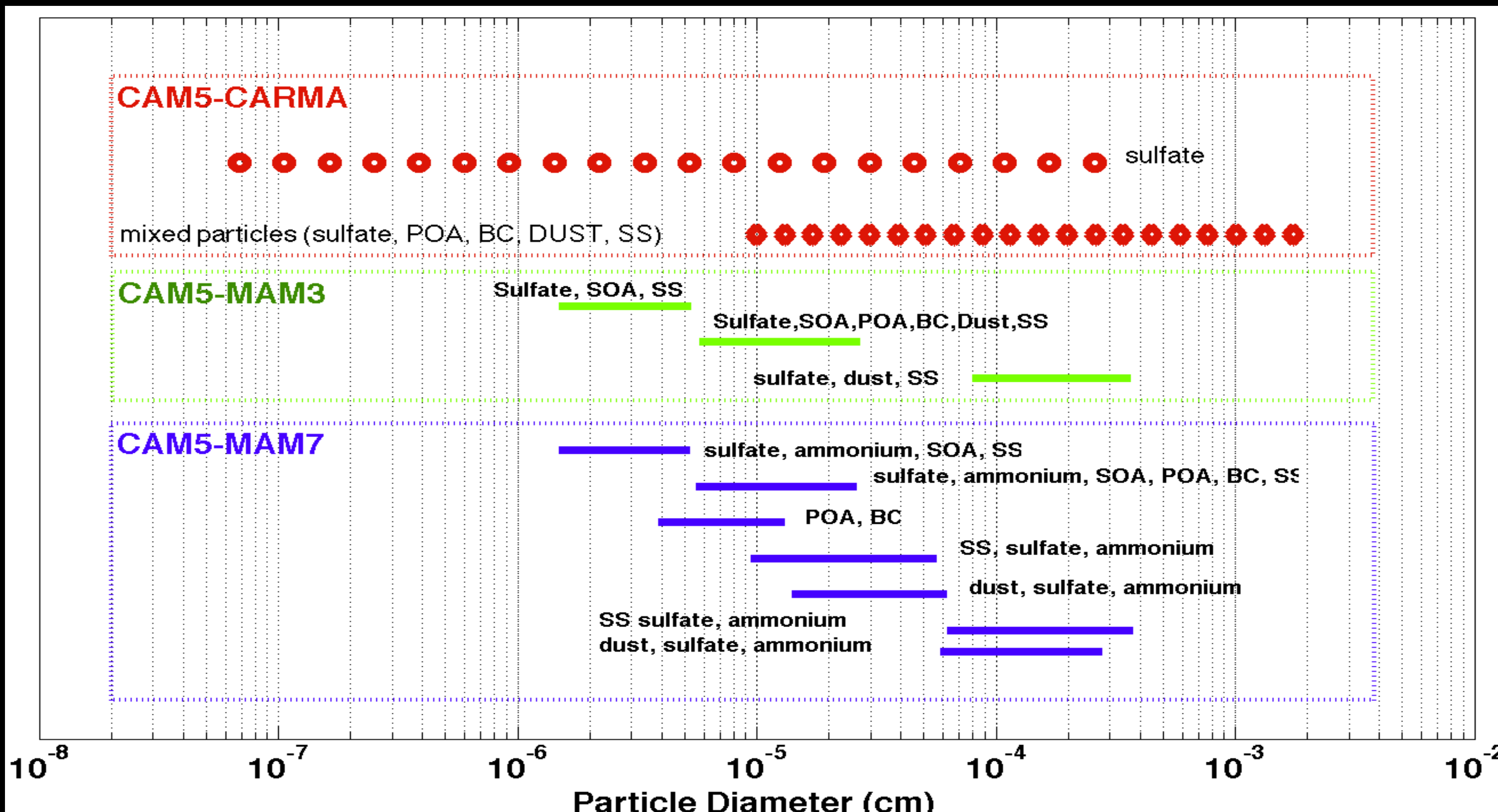
# Aerosols have a range of compositions and particle sizes





# CESM/CARMA size resolution compared with MAM




Yu et al , J Adv. Model. Earth Sys. 7, 865,doi10.1002/2014MS000421, 2015

# CARMA consumes 2 times more computing hours than CAM5/MAM7

| Model | CAM5/ CARMA3.0 | CAM5/ CARMA3.0 | CAM5/ MAM7 | CAM5/ MAM3 | CAM5/ MAM7* |
|---|---|---|---|---|---|
| Resolution | 1.9x2.5, 30 vertical levels | | | | |
| Gas phase chemistry | CAM-Chem | CAM-Chem | CAM-Chem | CAM-Chem | x |
| Chemical reactions # | 234 | 234 | 210 | 210 | 7 |
| Aerosol tracers # | 138 | 138 | 31 | 15 | 31 |
| Wall-clock hours | 8.5 hours/yr | 6.2 hours/yr | 3.1 hours/yr | 2.4 hours/yr | 1.6 hours/yr |
| CPU | 250 | 250 | 250 | 250 | 250 |
| Notes | SOA use VBS; including stratospheric sulfate chemistry | Don't re-compute coagulation kernels | Fixed yields for SOA | | fixed OH HO2 O3 NO3 |

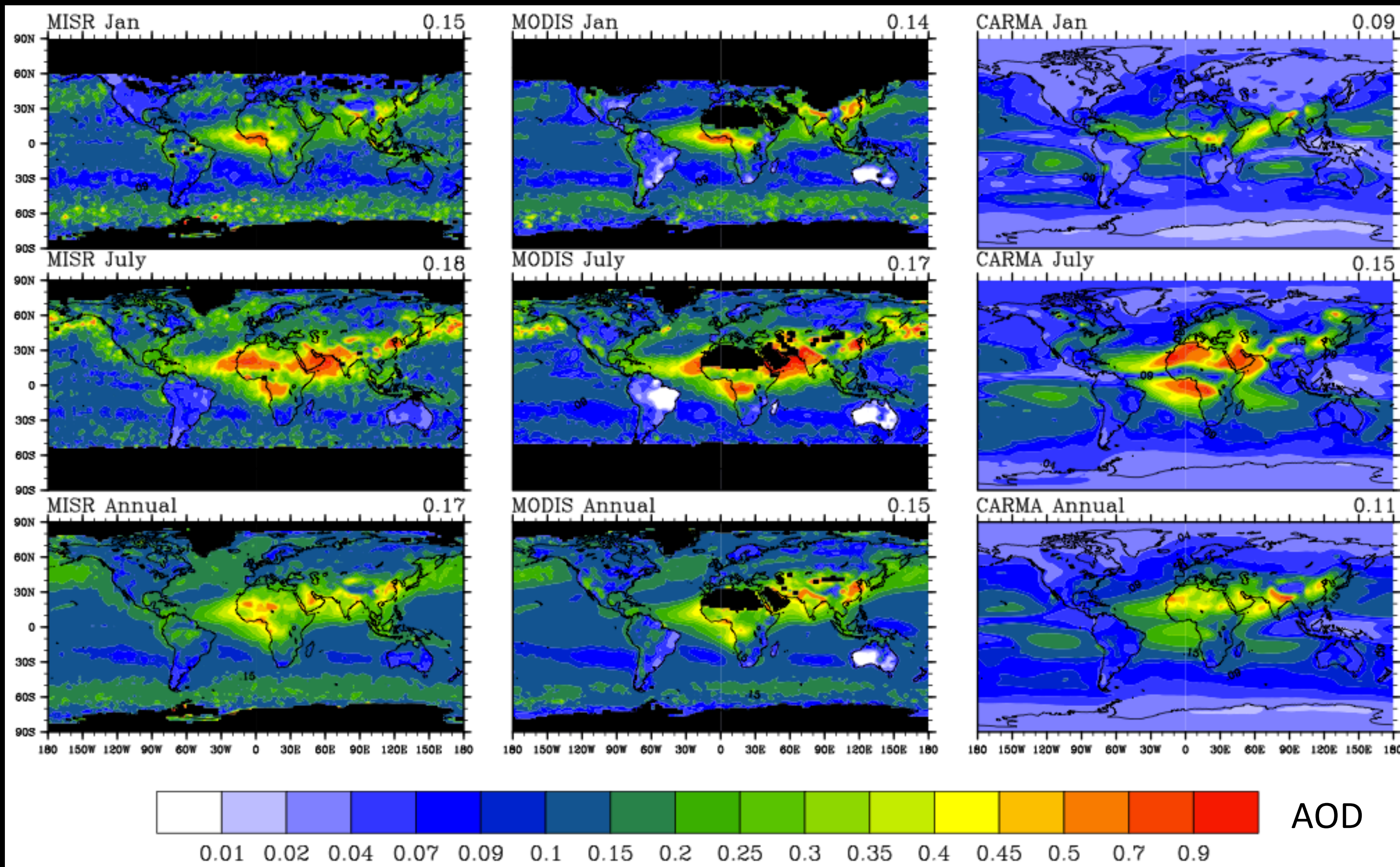
Yu et al , J Adv. Model. Earth Sys. 7, 865,doi10.1002/2014MS000421, 2015

# CARMA predicts similar aerosol burden with modal models, but with detailed size distribution

| POA | CARMA | MAM7 | BC | CARMA | MAM7 |
|---|---|---|---|---|---|
| ***Source*** Tg/y | 162.3 | 50.2 | ***Source*** Tg/y | 13.02 | 7.76 |
| ***Burden*** Tg | 1.29 | 0.68 | ***Burden*** Tg | 0.11 | 0.093 |
| ***Lifetime*** days | 2.9 | 4.9 | ***Lifetime*** days | 3.08 | 4.37 |
| **SOA** | **CARMA** | **MAM7** | **DUST** | **CARMA** | **MAM7** |
| ***Source*** Tg/y | 116.9 | 103.3 | ***Source*** Tg/y | 2900.34 | 2943.5 |
| ***Burden*** Tg | 1.1 | 1.15 | ***Burden*** Tg | 10.12 | 24.7 |
| ***Lifetime*** days | 3.43 | 4.08 | ***Lifetime*** days | 1.27 | 3.07 |
| **SALT** | **CARMA** | **MAM7** | **Nss-sulfate** | **CARMA** | **MAM7** |
| ***Source*** Tg/y | 7183.1 | 5004.1 | ***Source*** Tg S/y | 46 | 45.7 |
| ***Burden*** Tg | 7.74 | 7.58 | ***Burden*** Tg S | 0.8 | 0.47 |
| ***Lifetime*** days | 0.4 | 0.55 | ***Lifetime*** days | 6.34 | 3.72 |

Yu et al , J Adv. Model. Earth Sys. 7, 865,doi10.1002/2014MS000421, 2015

# CARMA captures global AOD spatial distribution, but lower AOD compared with satellites

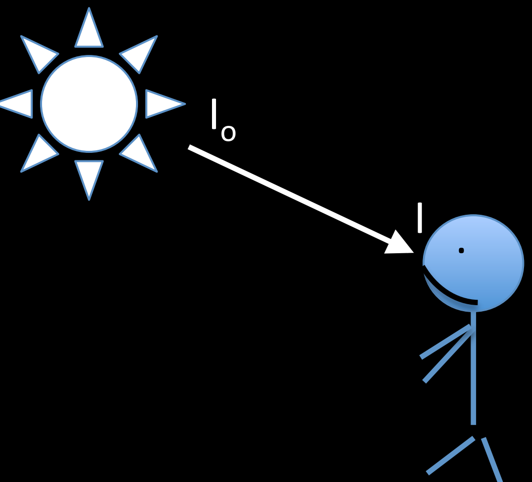



Yu et al , J Adv. Model. Earth Sys. 7, 865,doi10.1002/2014MS000421, 2015

# Need to know three things to calculate radiation field

## 1. AOD (AOT) = Aerosol extinction Optical Depth (Thickness)

1. Extinction optical depth



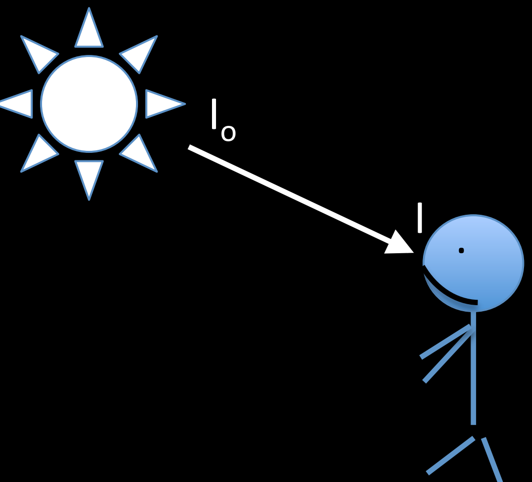

$$\tau_{e/\cos\theta} = \ln (I/I_o)$$

θ=zenith angle

# Need to know three things to calculate radiation field

## 2. Aerosol absorption or scattering optical depth or single scattering albedo

1. Extinction optical depth




$$\tau_{e/\cos\theta} = \ln (I/I_o)$$

$\theta$=zenith angle

2. Absorption or scattering optical depth, single scatter albedo

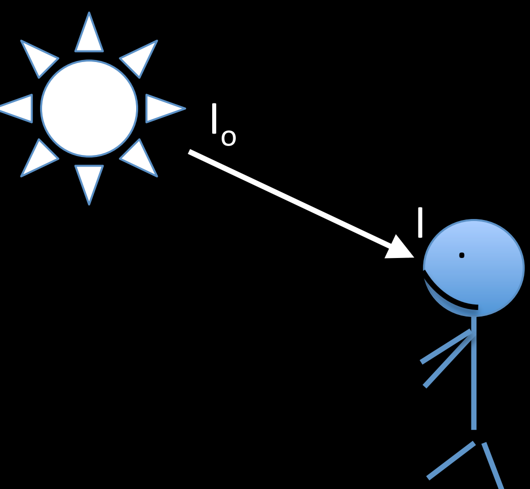
$$\tau_e = \tau_a + \tau_s$$

$$\omega_0 = \tau_s / \tau_e$$

# Need to know three things to calculate radiation field

## 3. Scattering phase function

1. Extinction optical depth



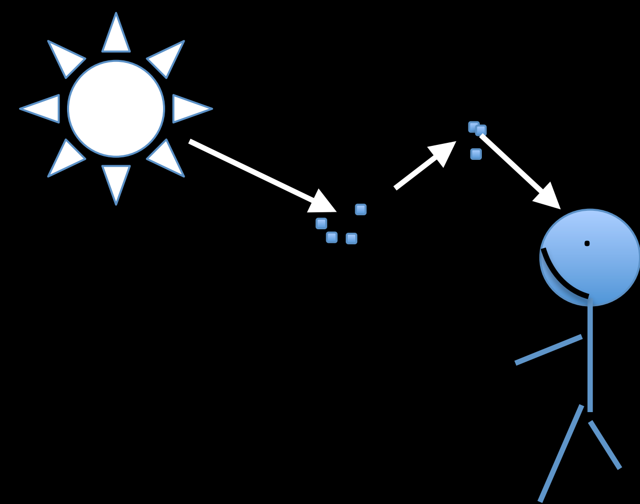

$$\tau_{e/\cos\theta} = \ln(I/I_o)$$

$\theta$=zenith angle

2. Absorption or scattering optical depth

$$\tau_e = \tau_a + \tau_s$$

3. Scattering phase function



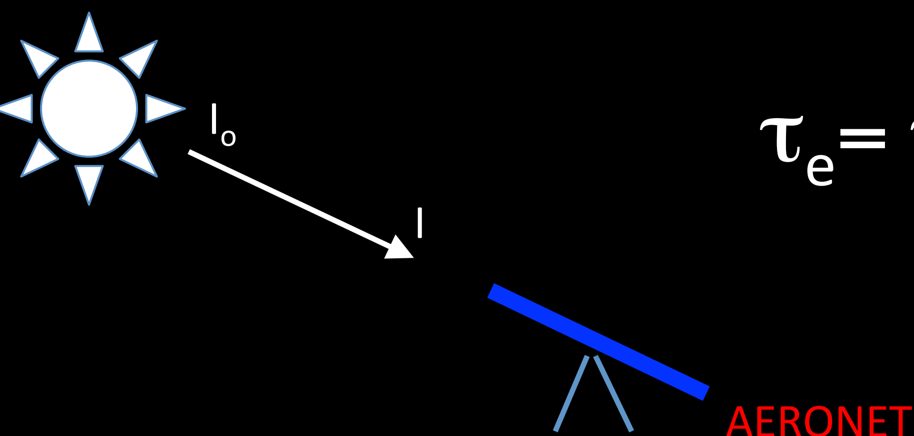
# AOD (AOT) = Aerosol extinction Optical Depth (Thickness)

## We can measure the optical depth

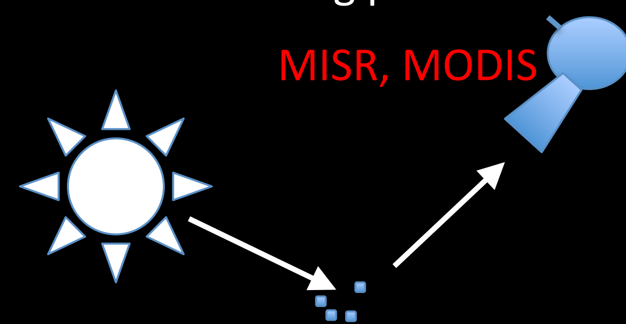
1. Extinction optical depth

2. Absorption or scattering optical depth

3. Scattering phase function




$$\tau_e = \tau_a + \tau_s$$

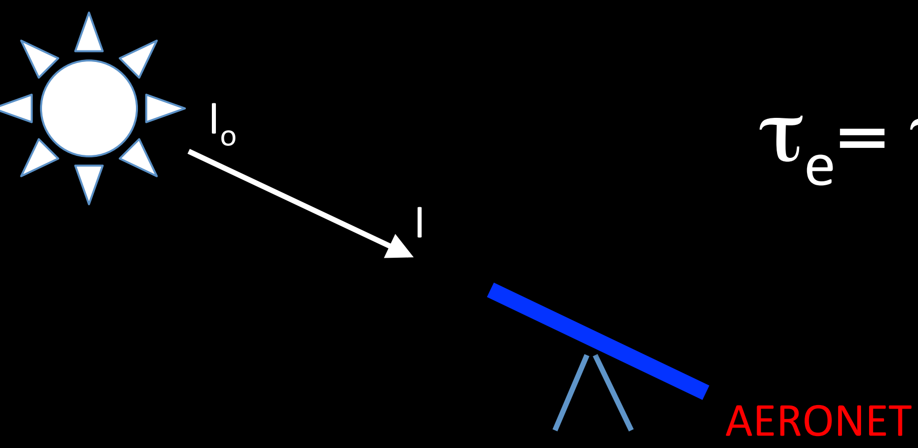



$$\tau_{e/\cos\theta} = \ln(I/I_o)$$

# AOD (AOT) = Aerosol extinction Optical Depth (Thickness)

## Satellites can measure the AOD

1. Extinction optical depth

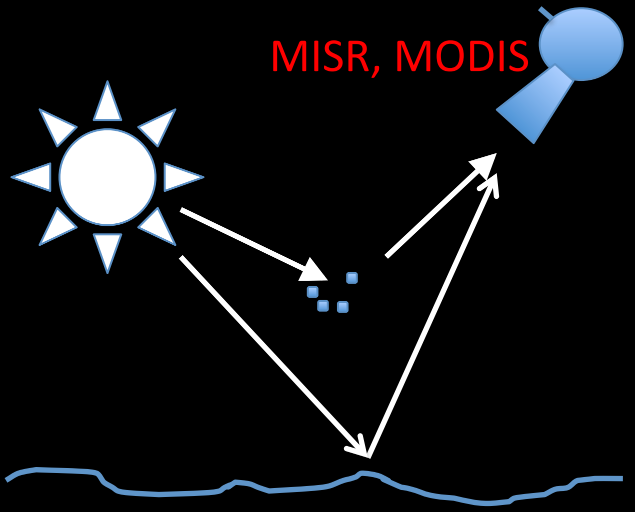



$$\tau_{e/\cos\theta} = \ln (I/I_o)$$

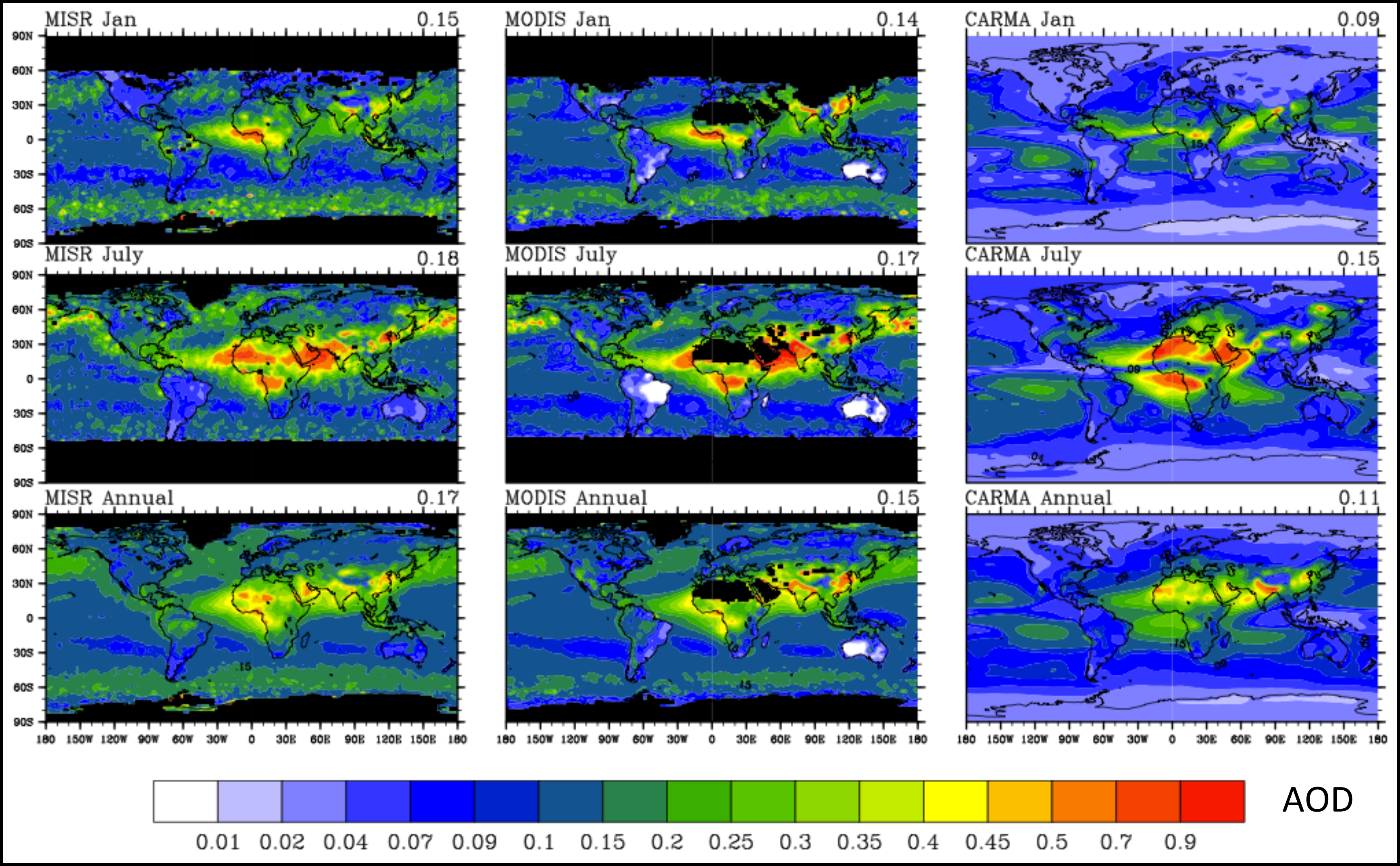
2. Absorption or scattering optical depth

$$\tau_e = \tau_a + \tau_s$$

3. Scattering phase function

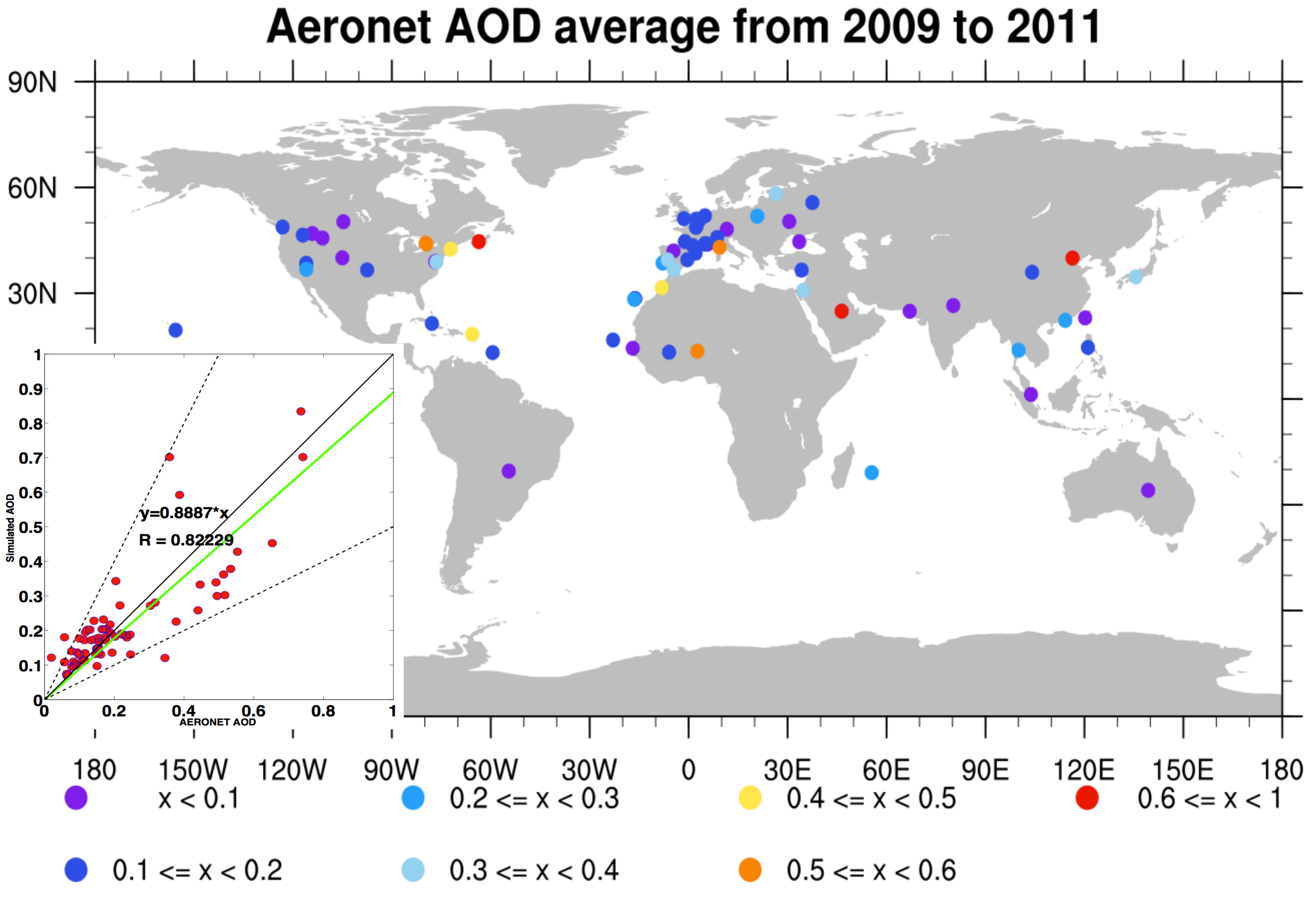


# CARMA captures global AOD spatial distribution, but lower AOD compared with satellites

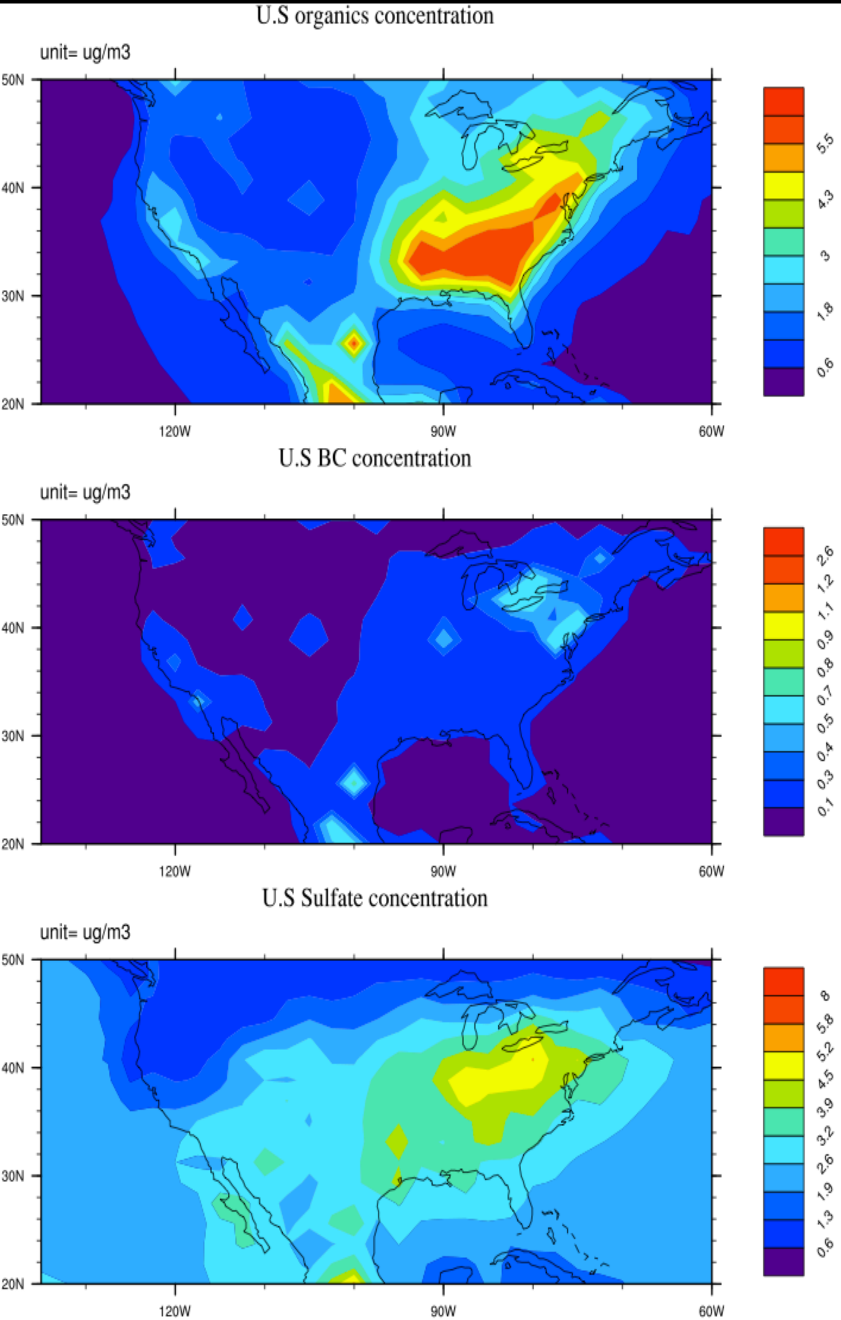


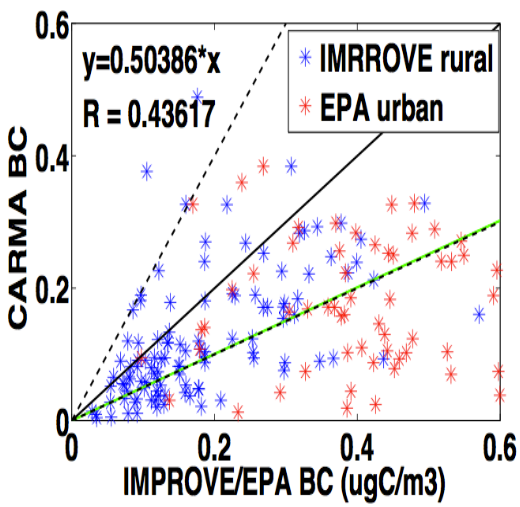

Yu et al , J Adv. Model. Earth Sys. 7, 865,doi10.1002/2014MS000421, 2015

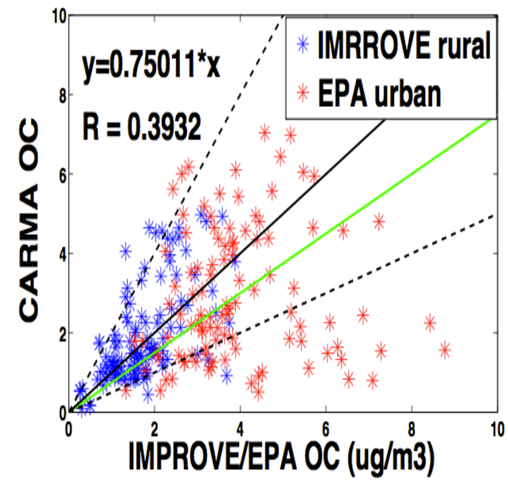
# Model captures 89% of AERONET AOD on average

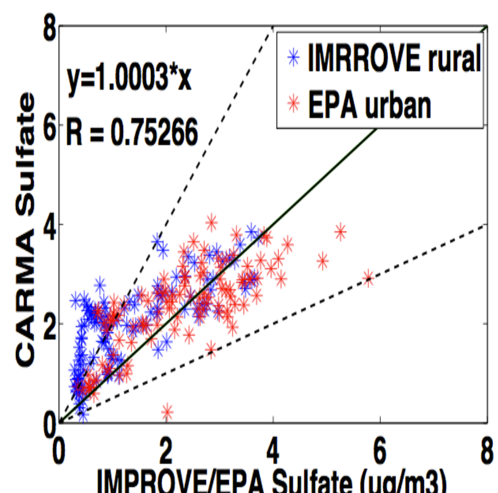


# Model reproduces OC, BC, Sulfate in U.S.



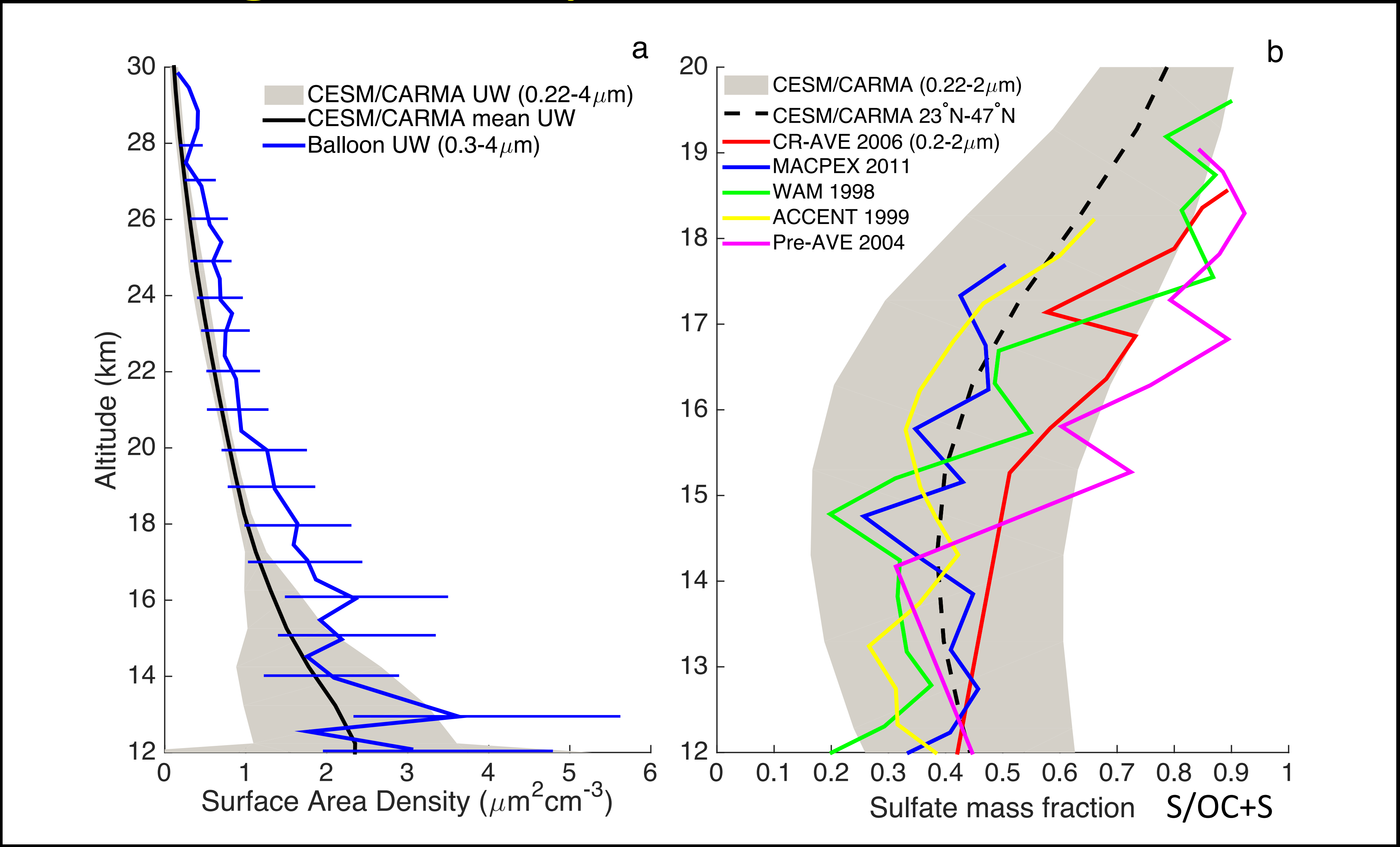

Yu et al , J Adv. Model. Earth Sys. 7, 865,doi10.1002/2014MS000421, 2015

# Radiative Forcing of Sulfate and Organics Reaching the Stratosphere

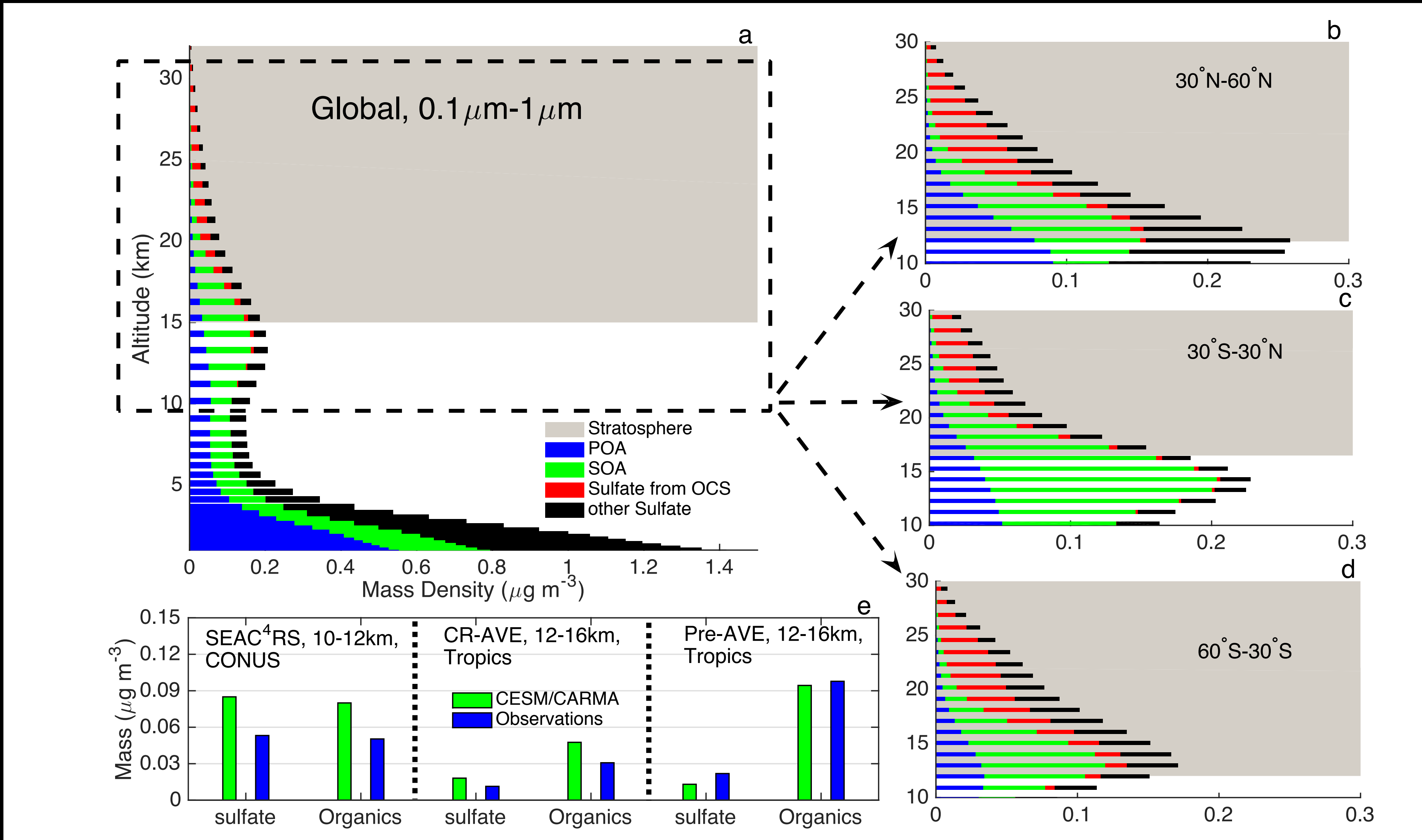
Pengfei Yu, Daniel M. Murphy, Robert W. Portmann, Owen B. Toon, Karl D. Froyd, Andrew W. Rollins, Ru-Shan Gao and Karen H. Rosenlof

Geophysical Research Letters, In press 2016

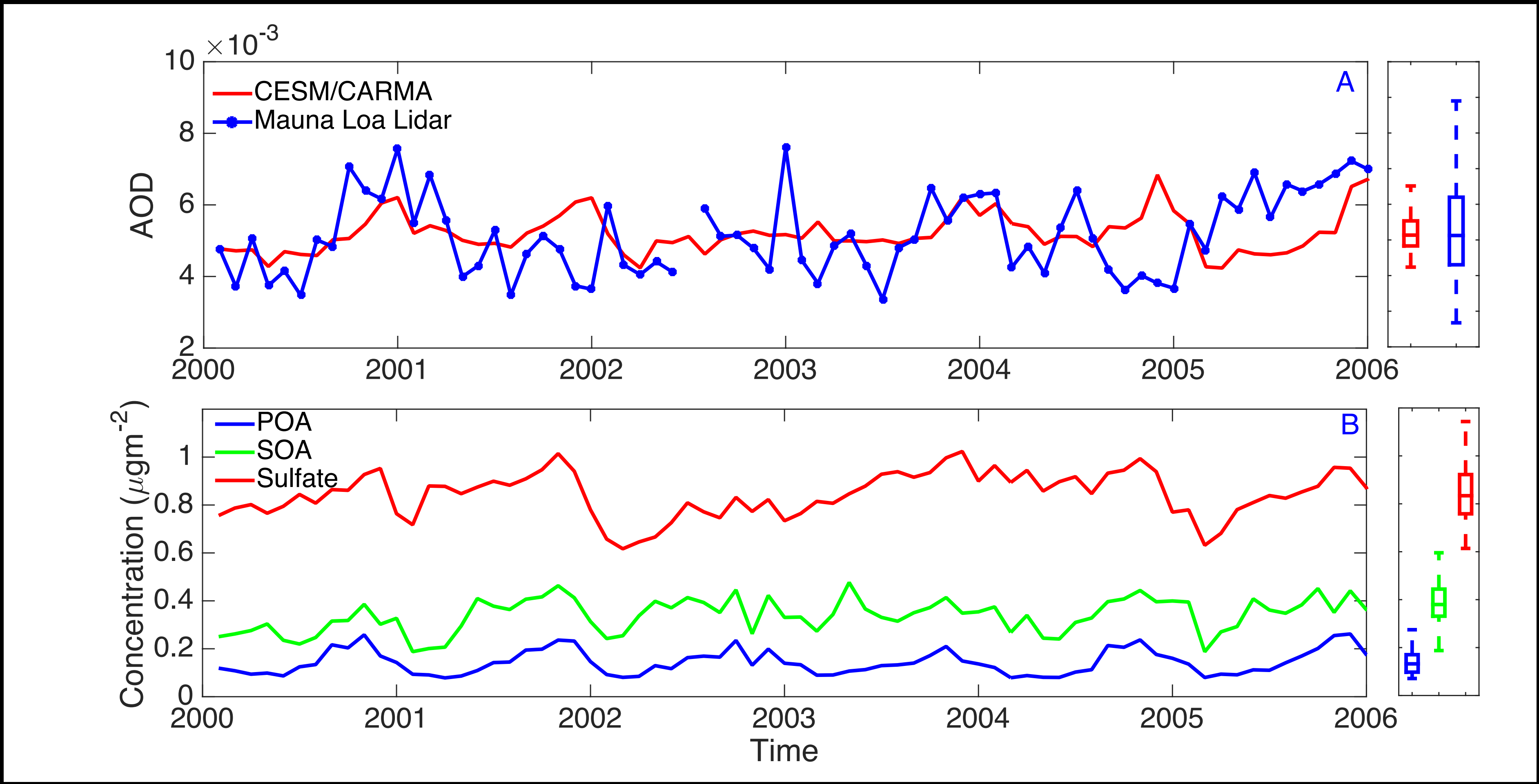
# Stratospheric aerosol contains a lot of organic compounds below 20 km



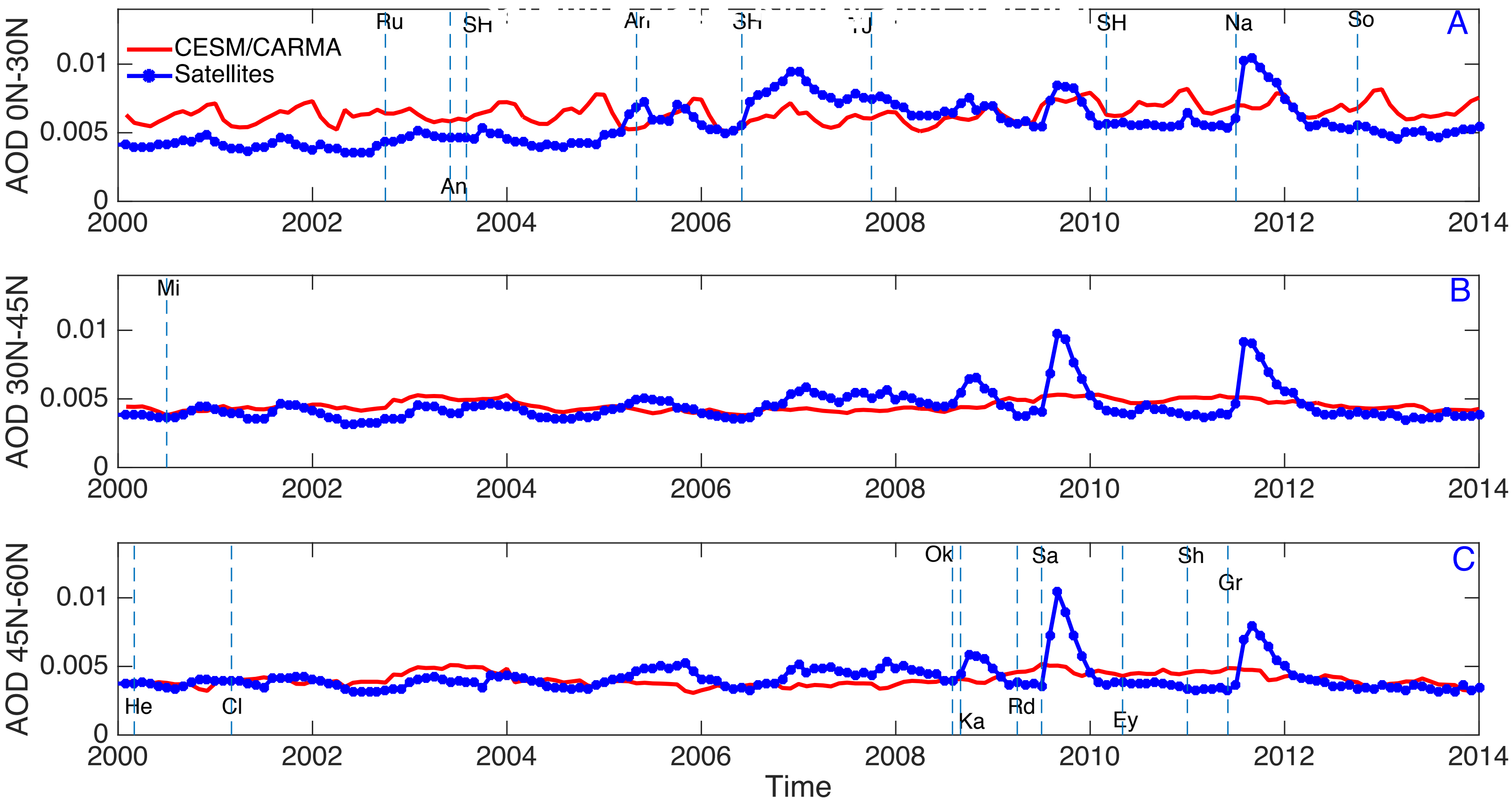
# Organics, and Sulfate in the Stratosphere



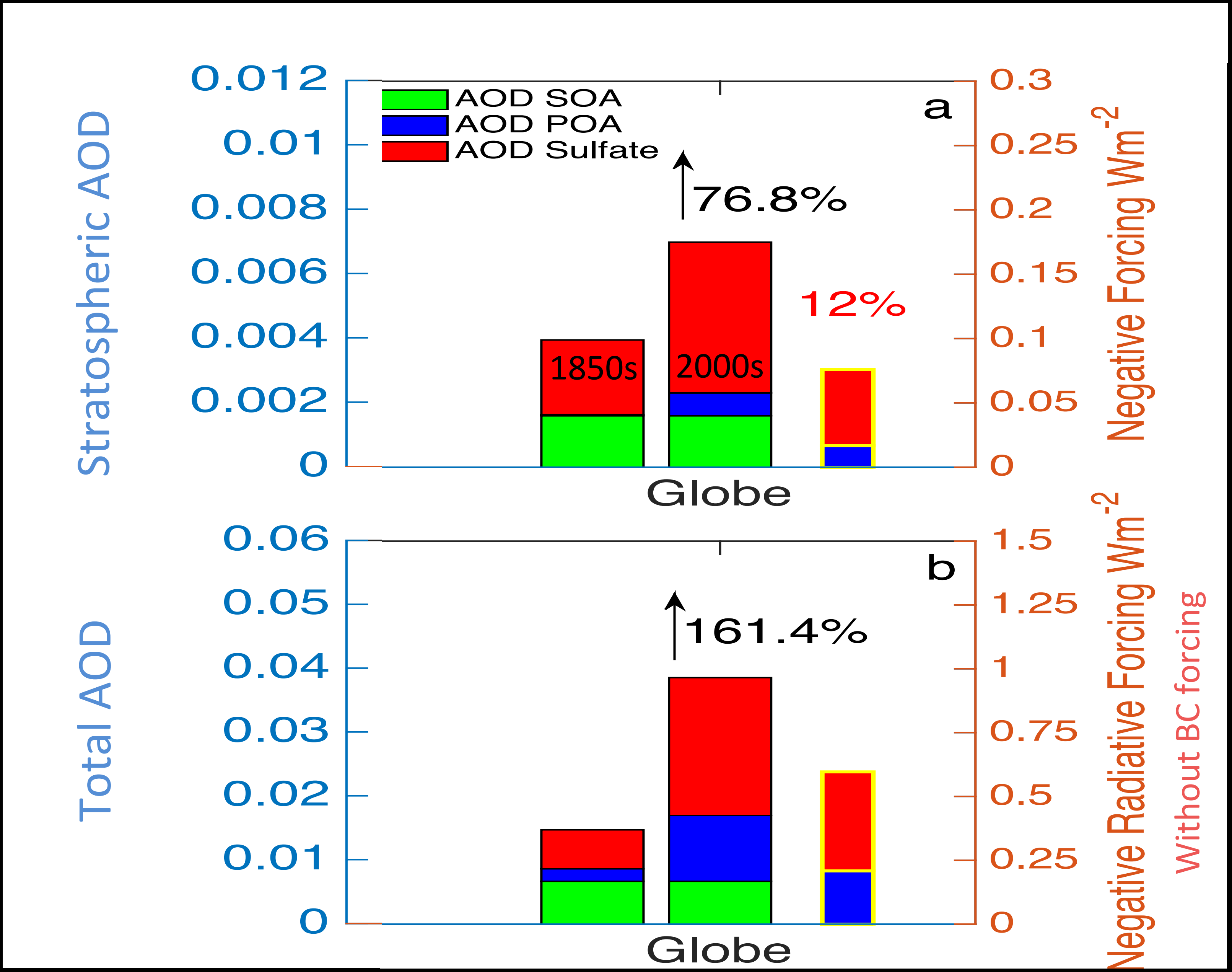
# Stratospheric AOD vs. Lidar



# Stratospheric AOD vs. Satellites



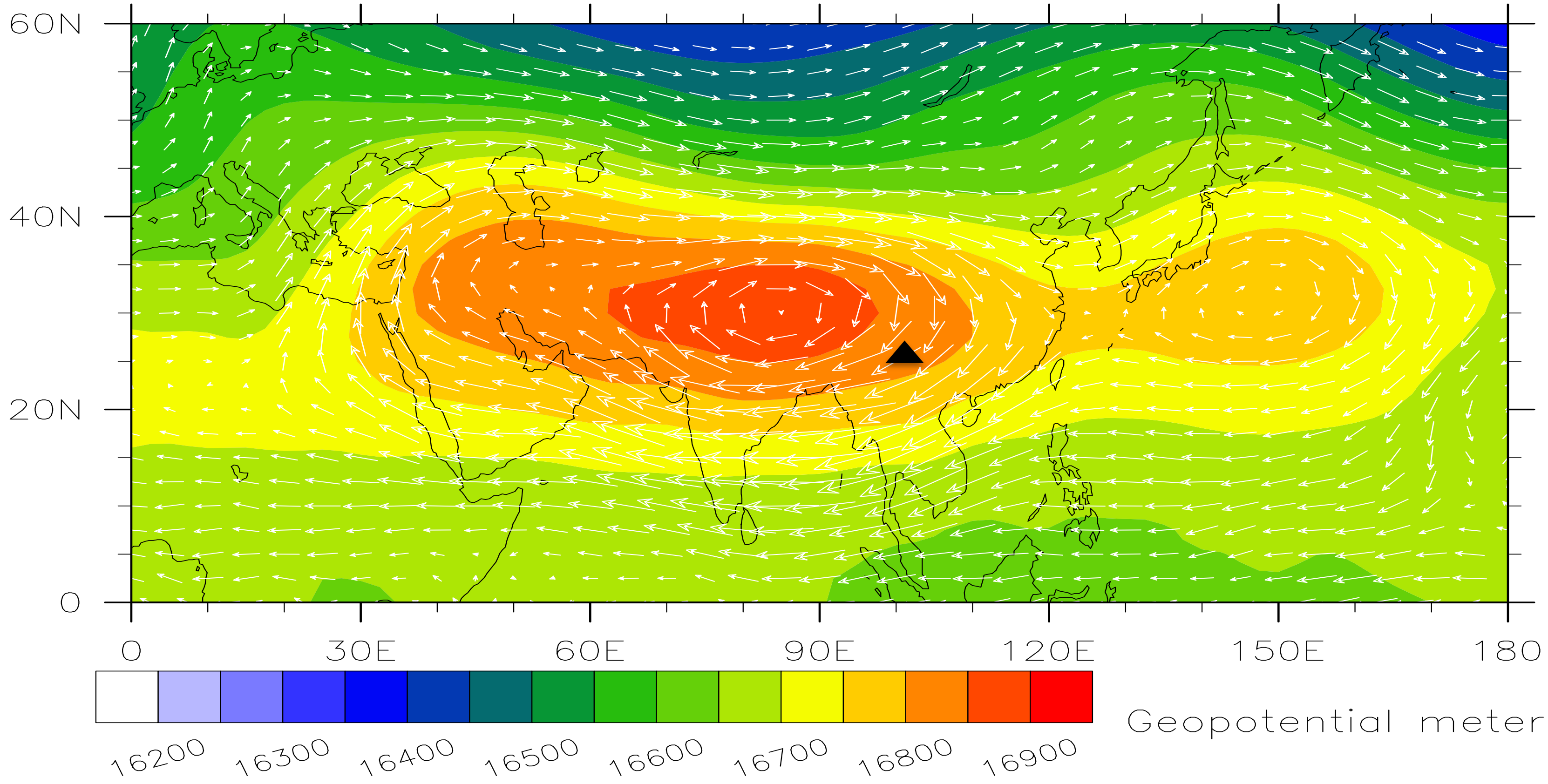
# Significant stratospheric radiative forcing



# Key points about radiative forcing by stratospheric aerosols

- Organics contribute to 30-40% of stratospheric aerosol burden.
- The increase in stratospheric aerosol optical depth (AOD) is about 12% of the total atmospheric AOD change since 1850.
- Change in radiative forcing from stratospheric aerosol is ~21% of the change in total direct aerosol radiative forcing since 1850.

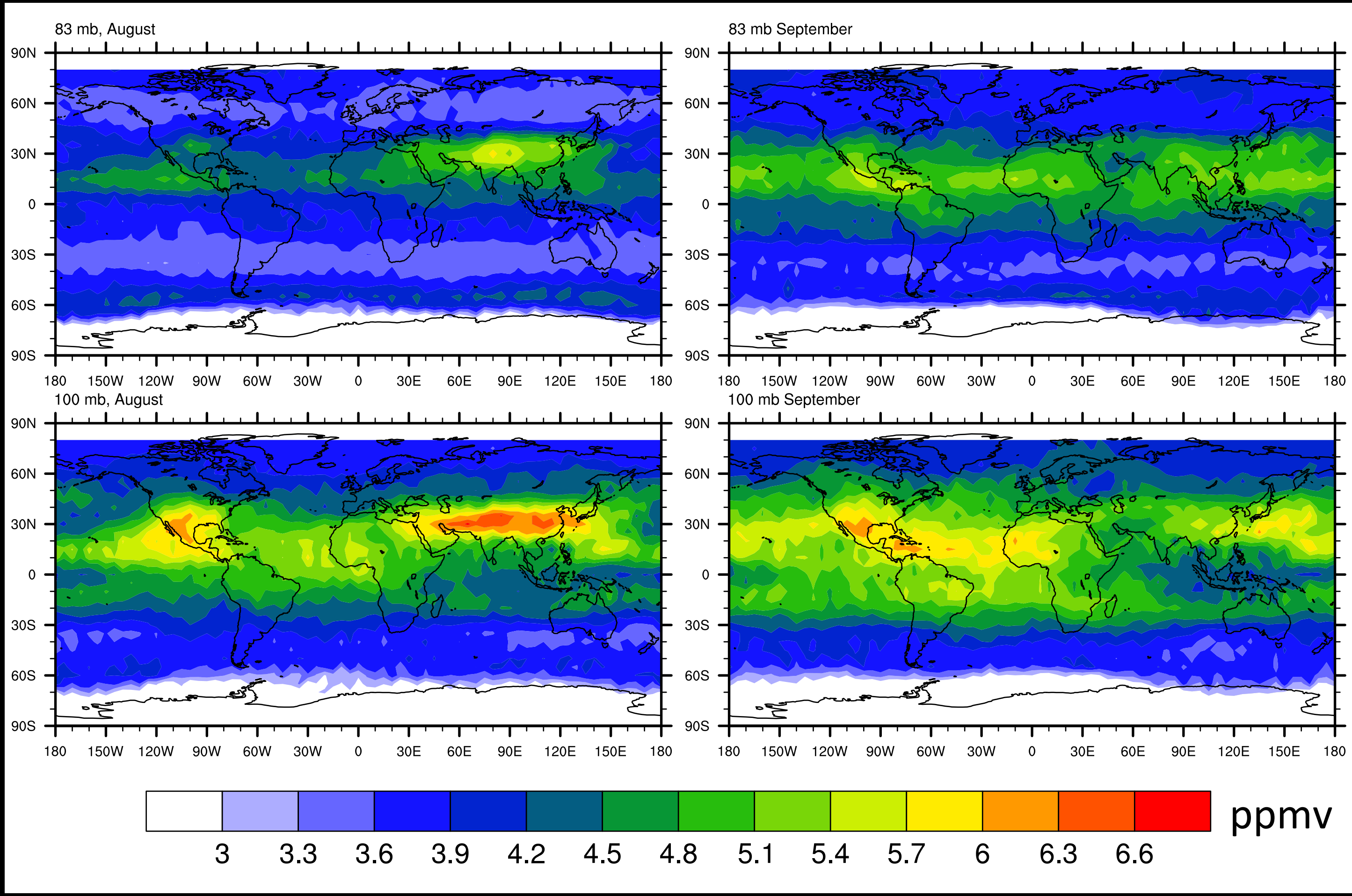
# Asian Summer Monsoon stands out on dynamical fields




100 hPa Geopotential height, m

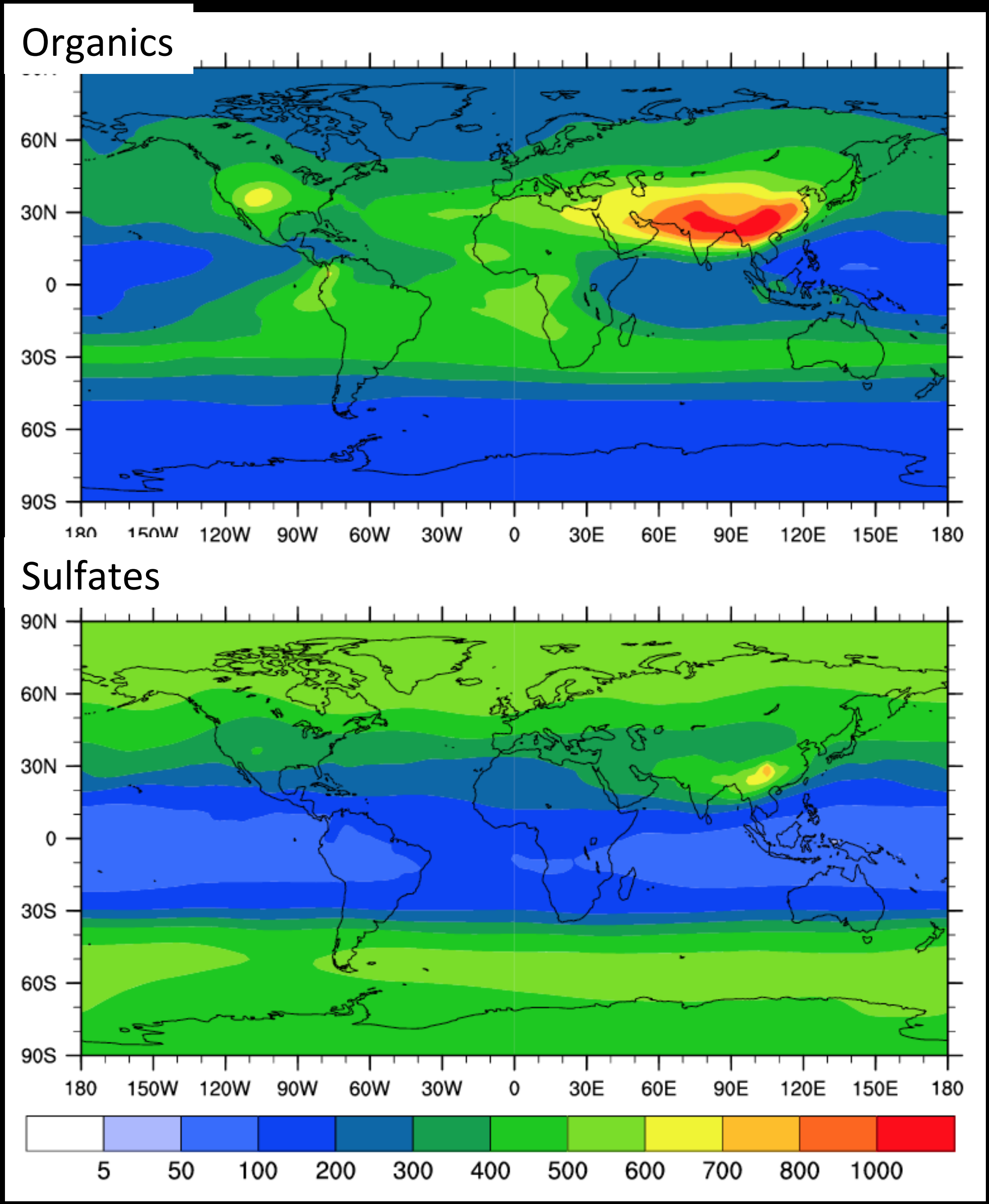
Yu et al , Geophys. Res. Lett., 42,2540, doi10.1002/2015GL063181,2015

# Asian Monsoon is wettest region of the UTLS in summer;
# HCN, CO, aerosols also observed



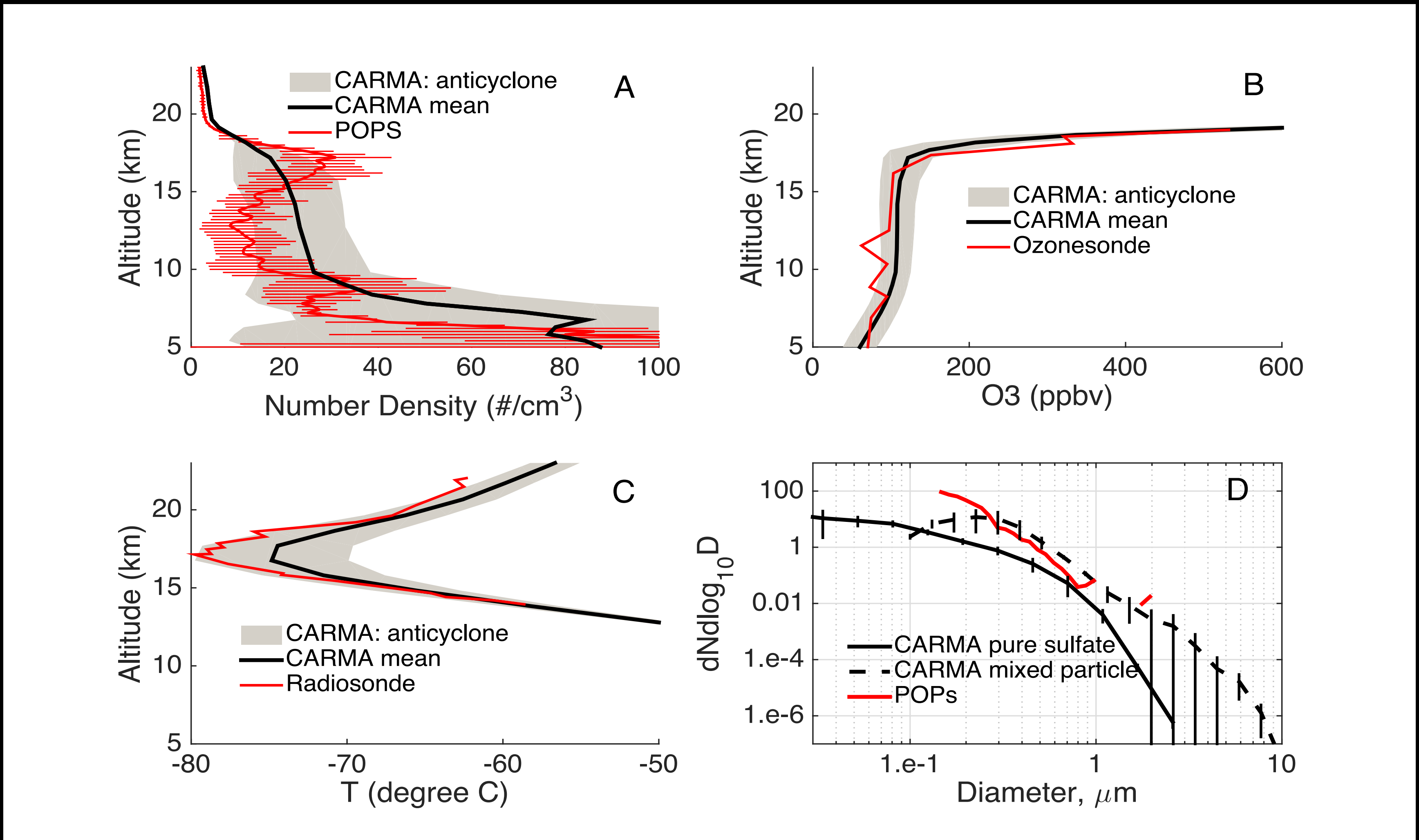

Yu et al , Geophys. Res. Lett., 42,2540, doi10.1002/2015GL063181,2015

# Observations and simulations show Asian Tropopause Aerosol Layer, ATAL



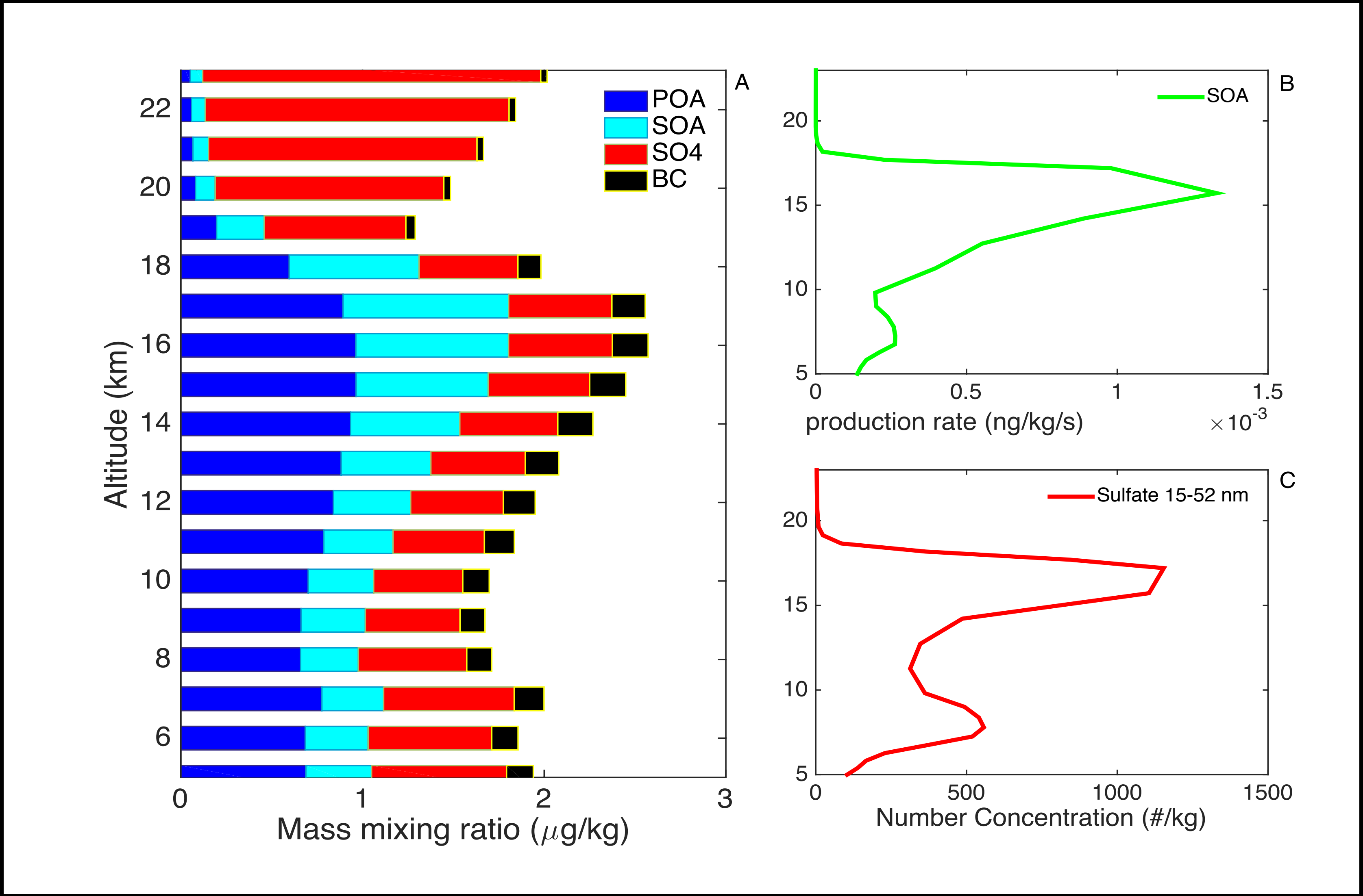

Yu et al , Geophys. Res. Lett., 42,2540, doi10.1002/2015GL063181,2015

# ATAL properties can be simulated



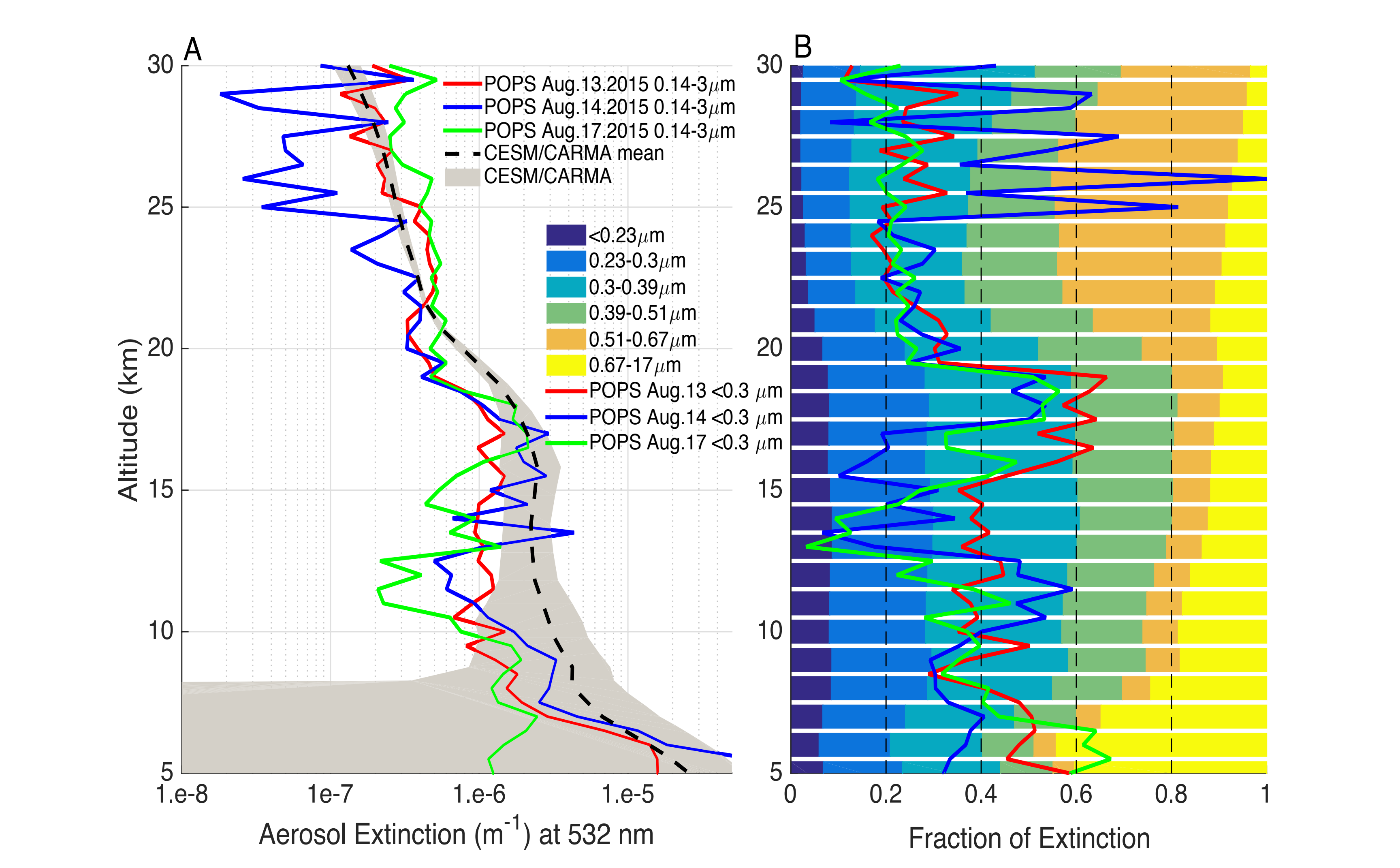

Yu et al , Geophys. Res. Lett., 42,2540, doi10.1002/2015GL063181,2015

# ATAL particles are partly formed in-situ




Yu et al , Geophys. Res. Lett., 42,2540, doi10.1002/2015GL063181,2015

# Limited optical contribution from small particles



# Key Results on ATAL

Satellites show Himalaya convection is lofting pollution into the UTLS.

Models can reproduce observed aerosol and gases.

Much of the lofted aerosol is composed of organics.

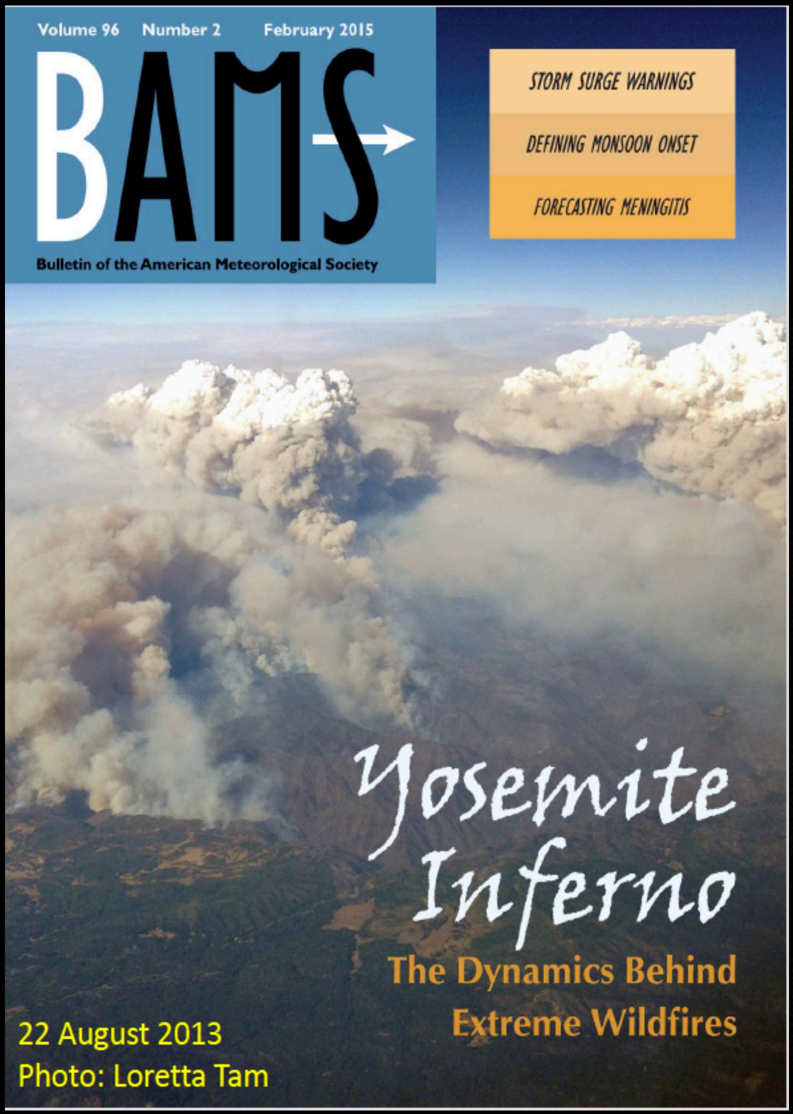
More data needed to understand composition of air and how it impacts the upper atmosphere.

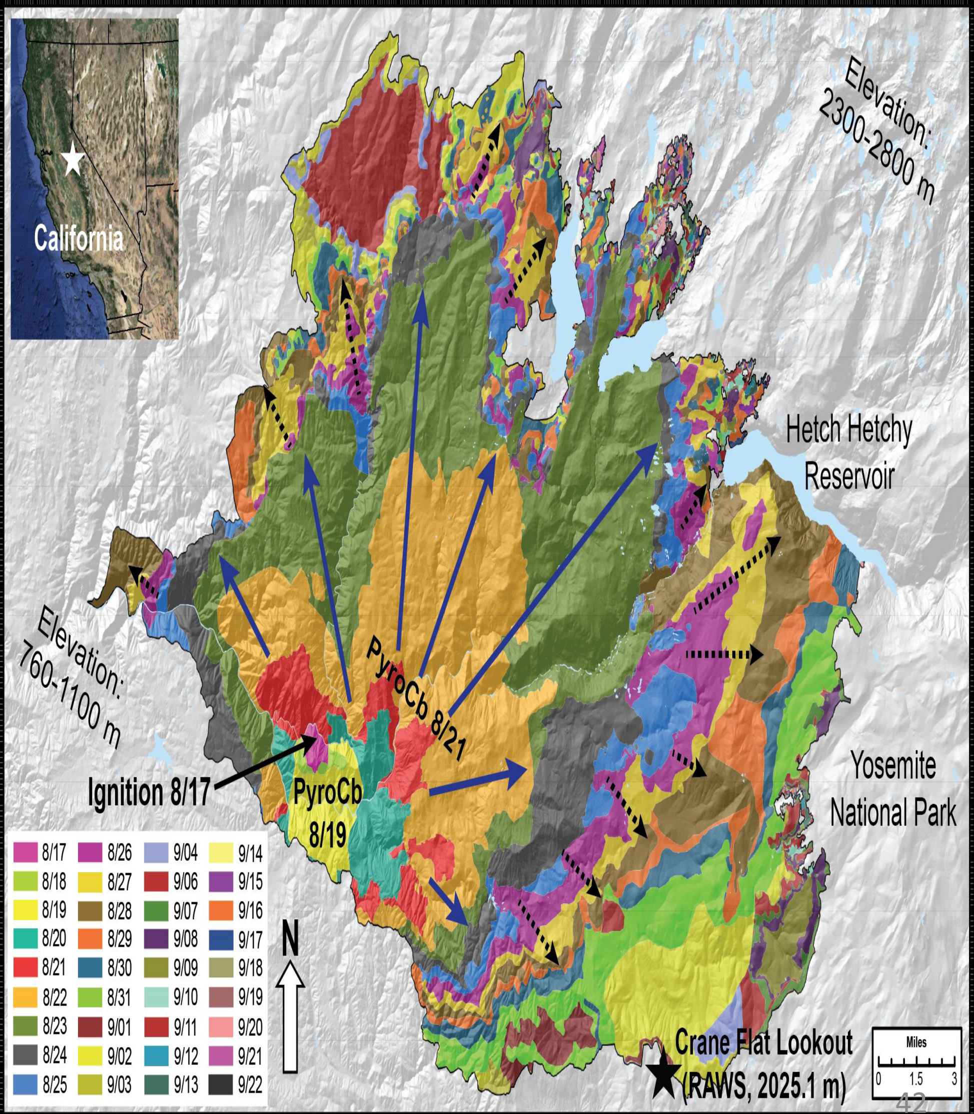
Balloon and aircaft flights are being considered by several groups.

# Surface Dimming by 2013 Rim Fire Smoke Simulated by a Sectional Aerosol Model

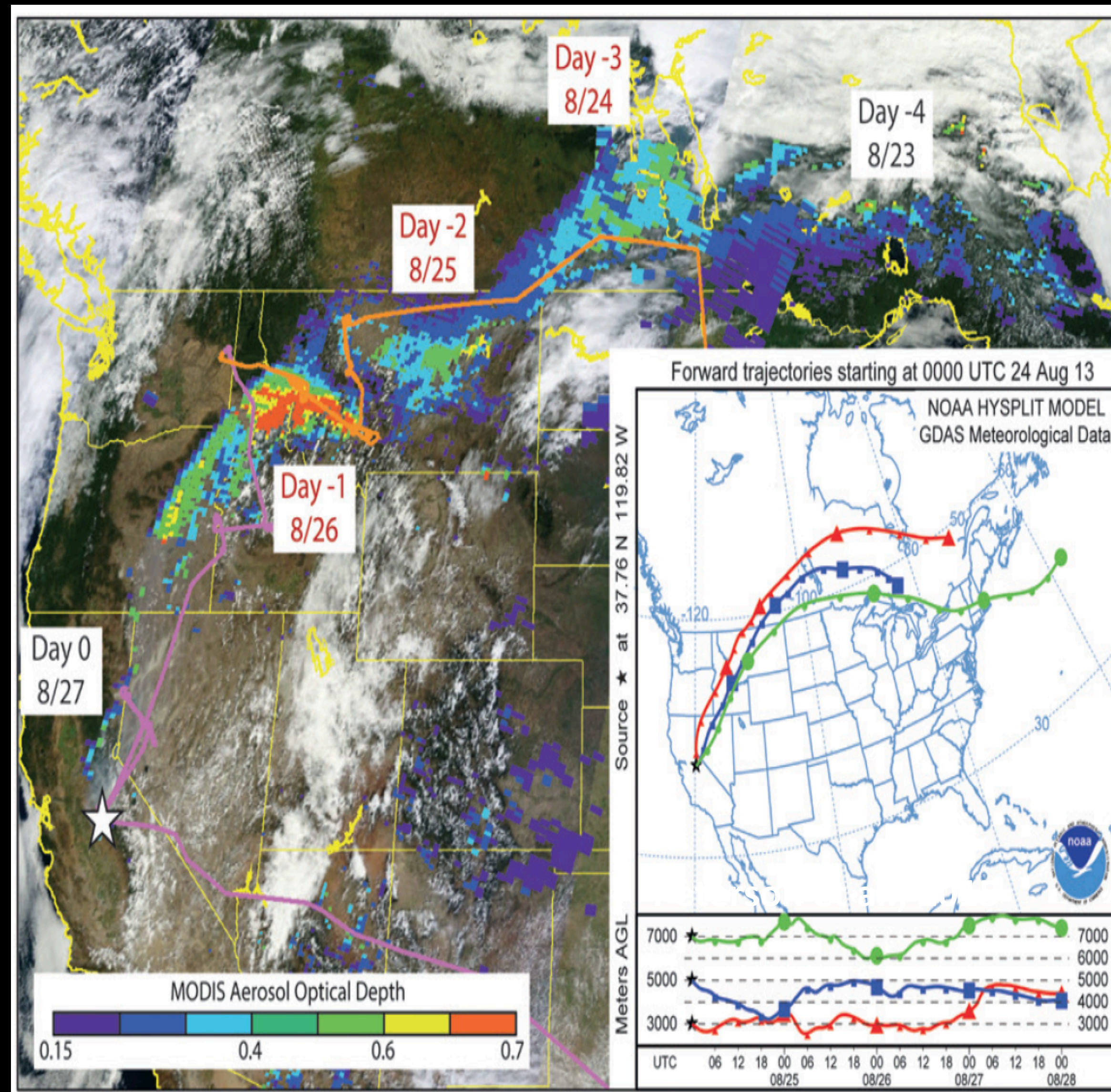
Yu et al., J. Geophysical Research, in press

# 2013 Rim fire burned third largest area in California history

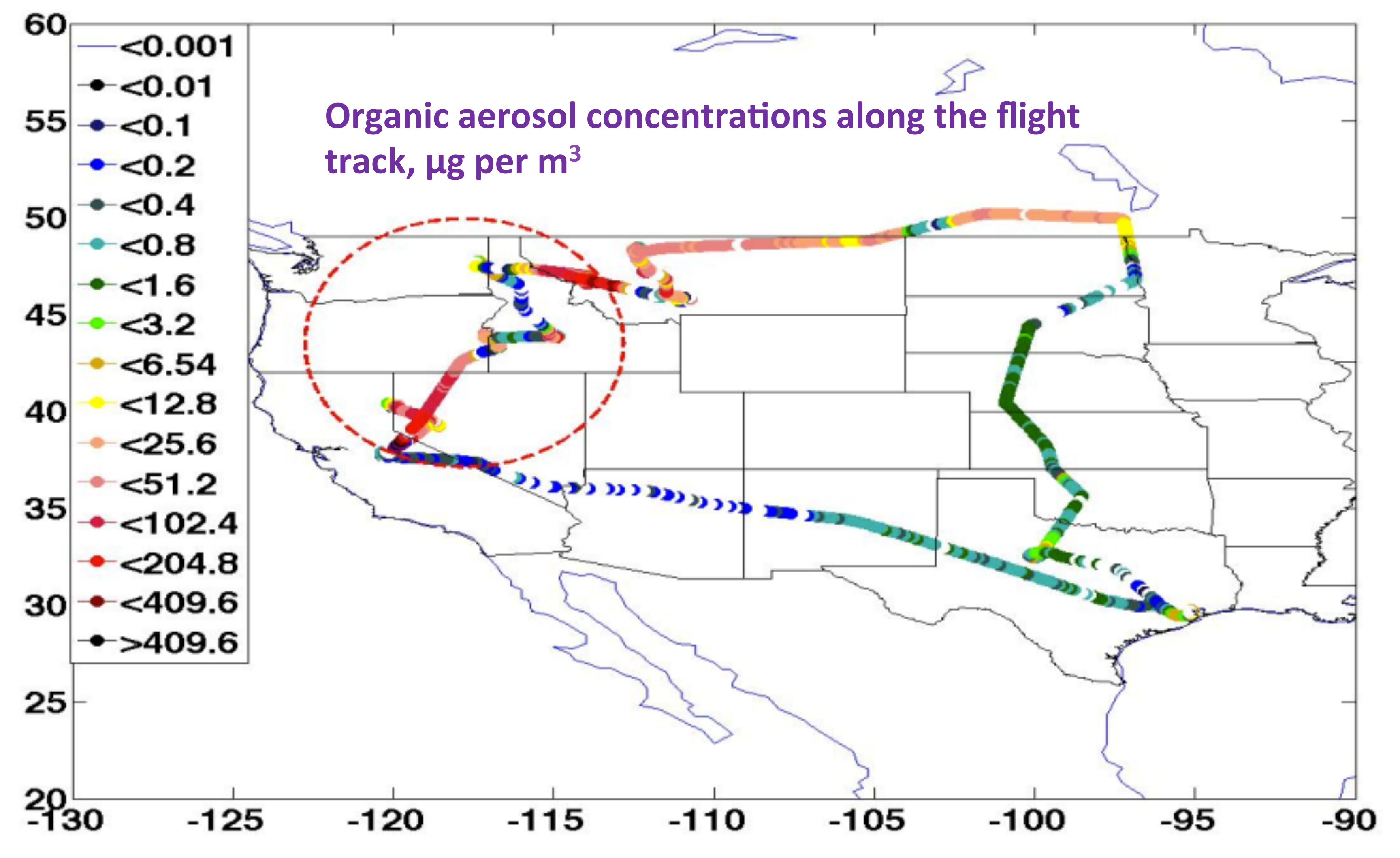


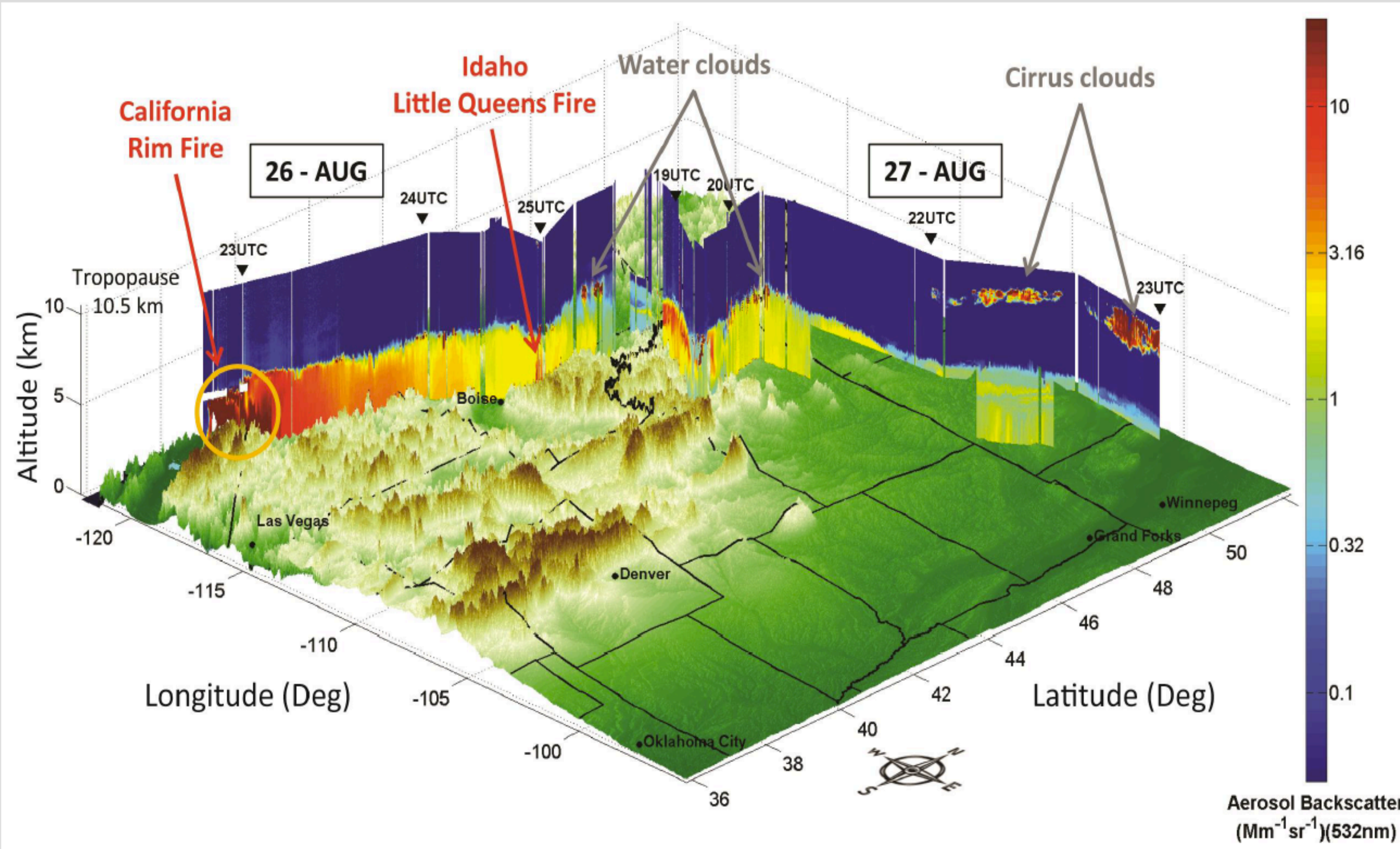
# MODIS shows transport of Rim Fire smoke

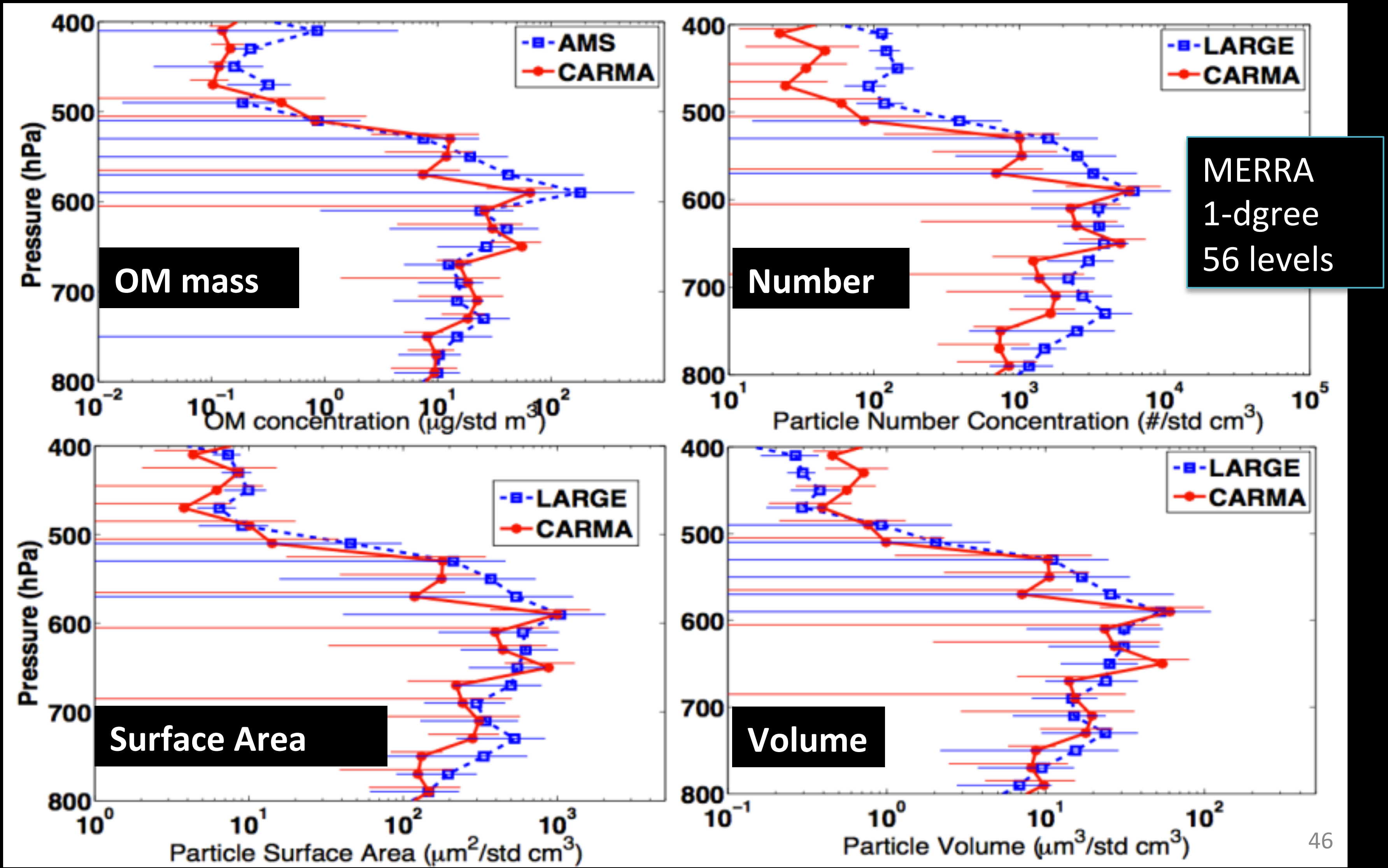
# We focus on smoke regions in red circle Aug. 26, and 27 flight of DC-8



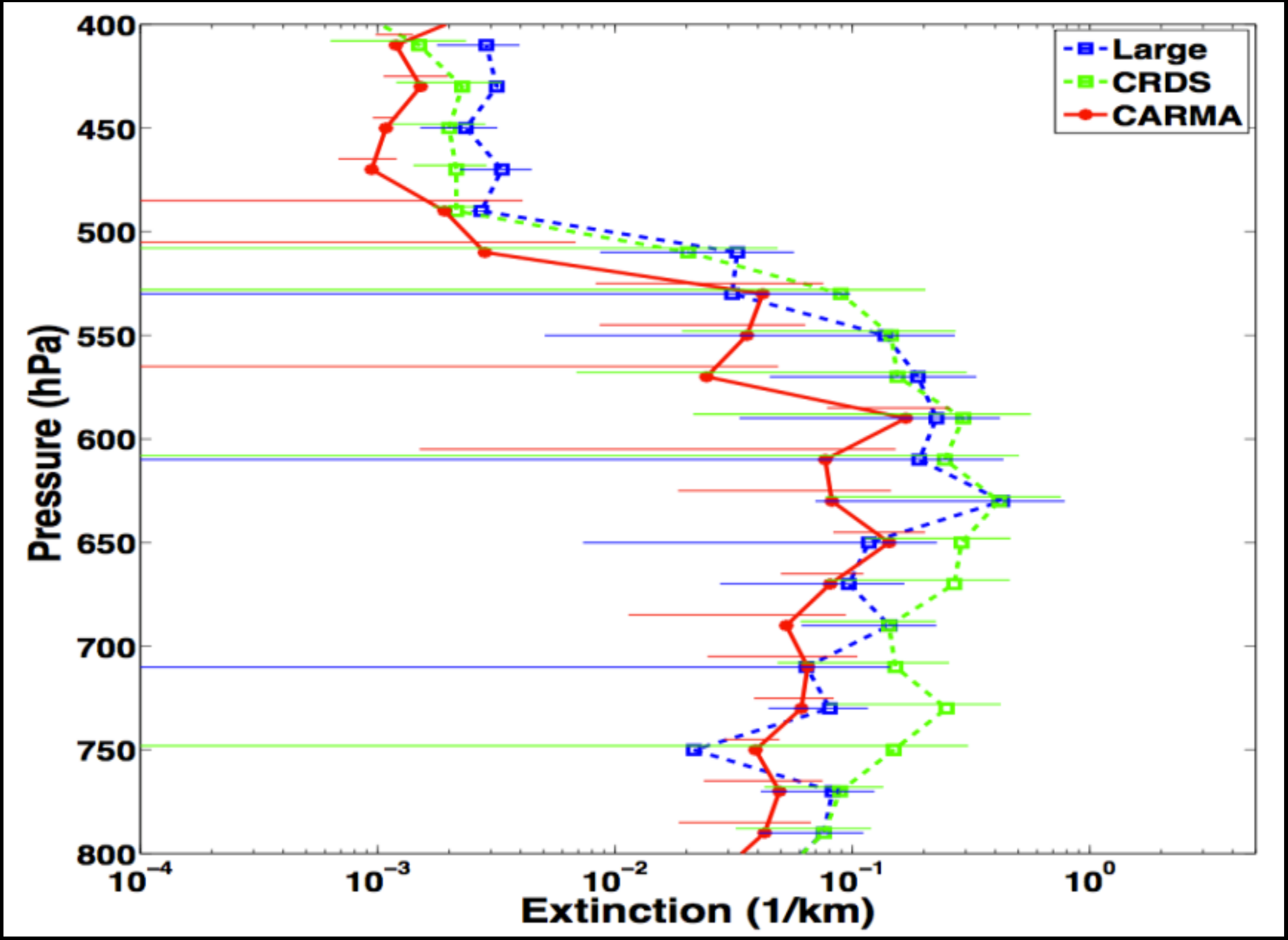
# Several fires happened simultaneously



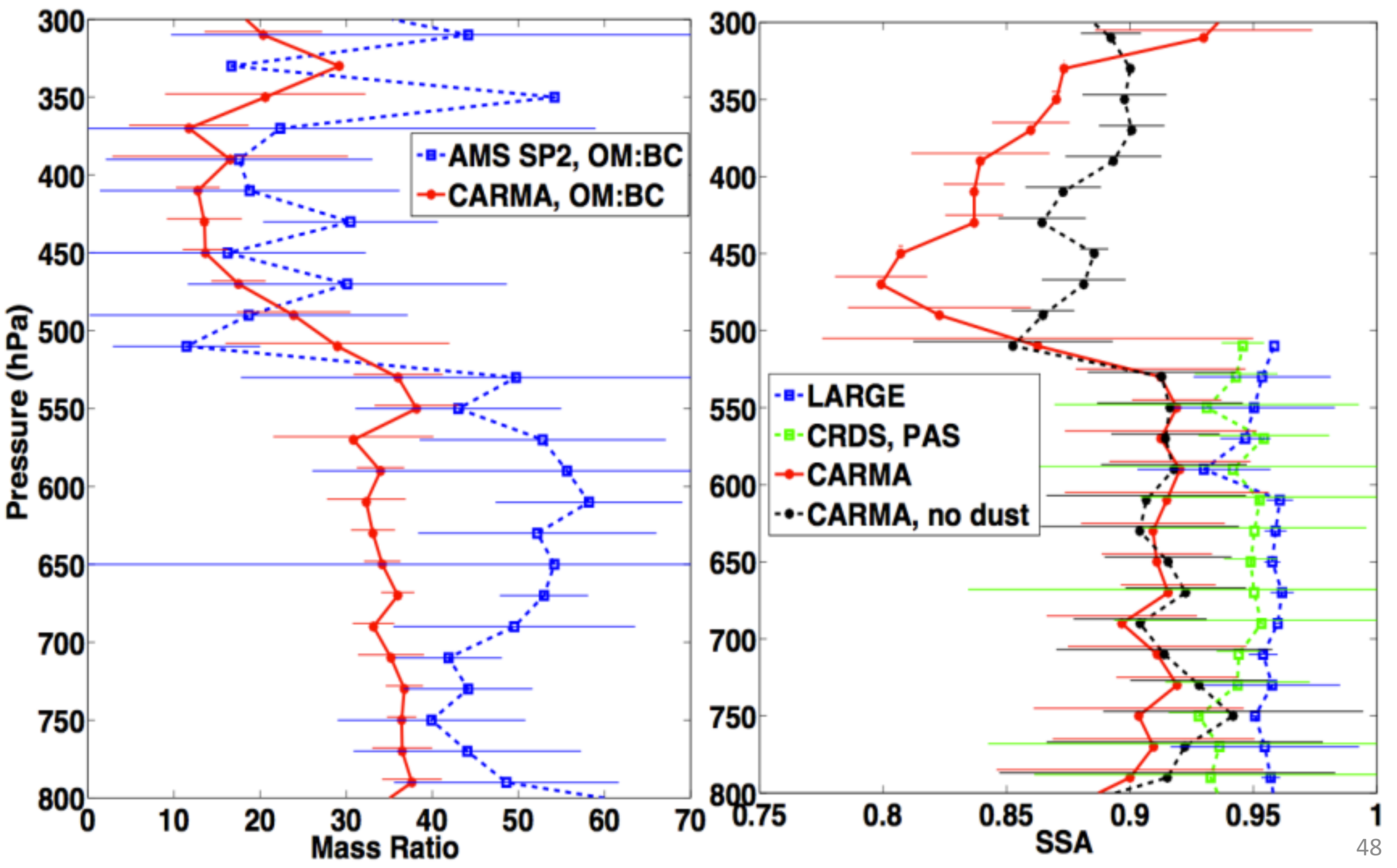
# Simulations are within error bars of different aerosol properties



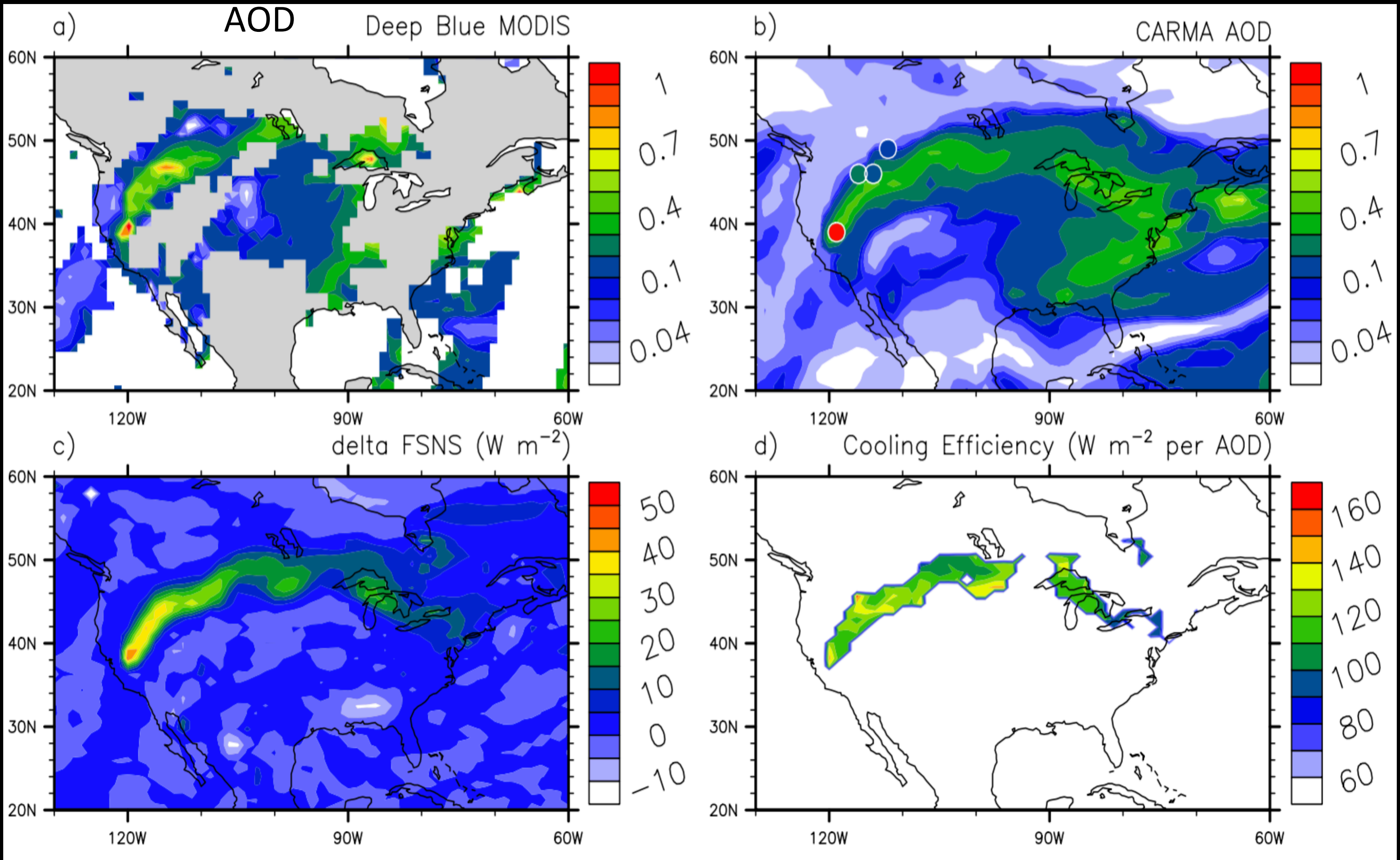
# Simulation underestimates aerosol extinction at altitude of the smoke



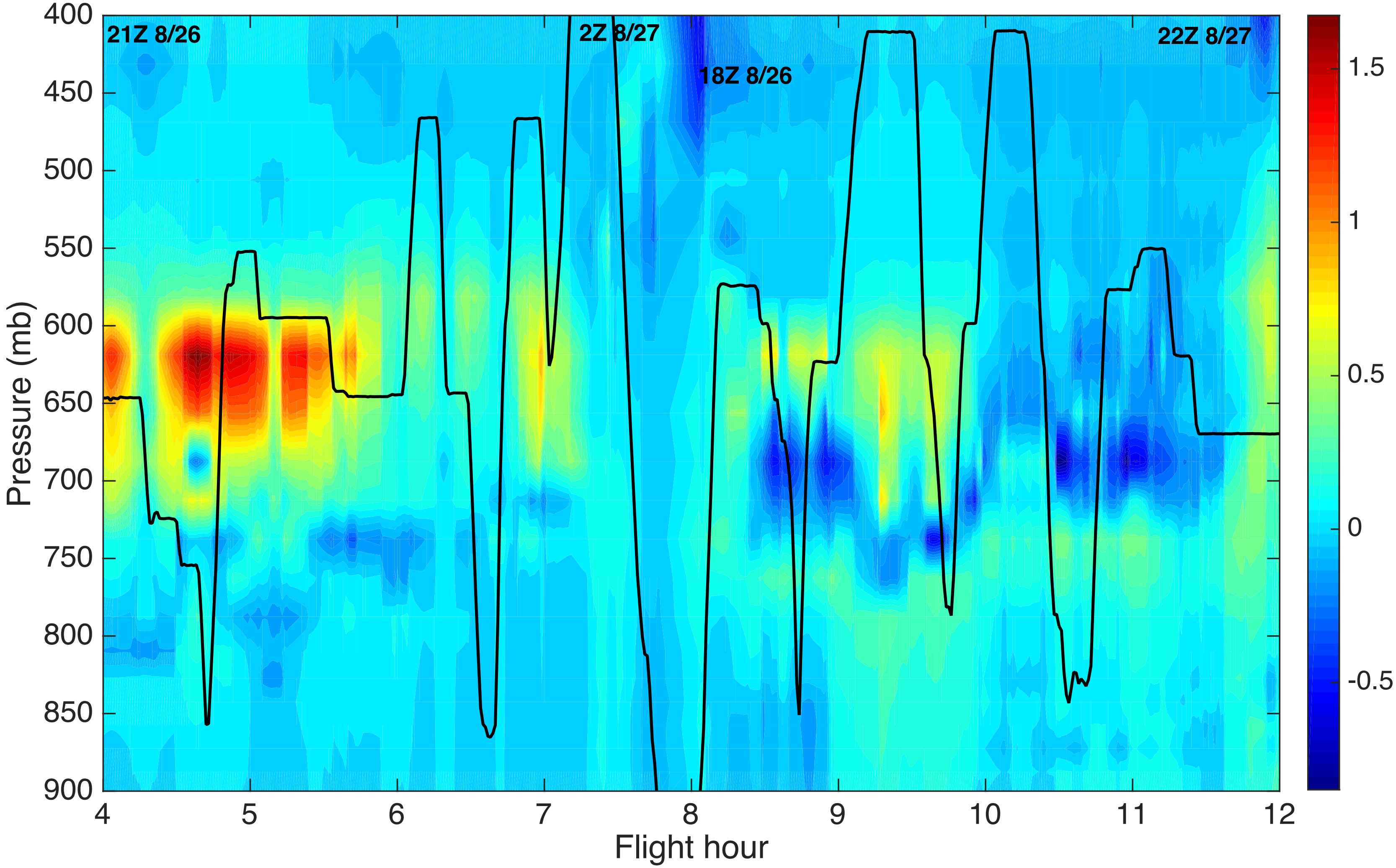
# Simulated SSA is lower than observed



# Simulated surface cooling efficiency: 120-150 W/m2 per AOD



# Simulated Peak Heating Rate: 1.7 K/day



# Summary

- CESM/CARMA documented in Yu et al. [2015, JAMES]
- CARMA simulation within data variability for Rim smoke.
- One-degree model can't resolve smoke near source
- Rim fire smoke injected up to 3 km above the ground
- CARMA finds smoke radiative cooling efficiency 130 $W/m^2$/AOD, within error bars of observations
- CARMA suggests Rim Fire smoke heats the air by 1.6 K/day, while observations suggest a value of 2.0 K/day.
- ATAL simulation shows much of the aerosol formed in-situ.
- Balloon and aircraft data needed to understand implications
- Organic aerosol is 30-40% of stratospheric aerosol burden.
- Stratospheric aerosol Radiative Forcing 25% of total from 1850

# What could you do?

- Many opportunities to work on improvements to models of clouds and aerosols.
- Many opportunities to measure aerosol properties, especially in regions that are undersampled.
- Many opportunities to work with local governments on pollution controls.


Question Time
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