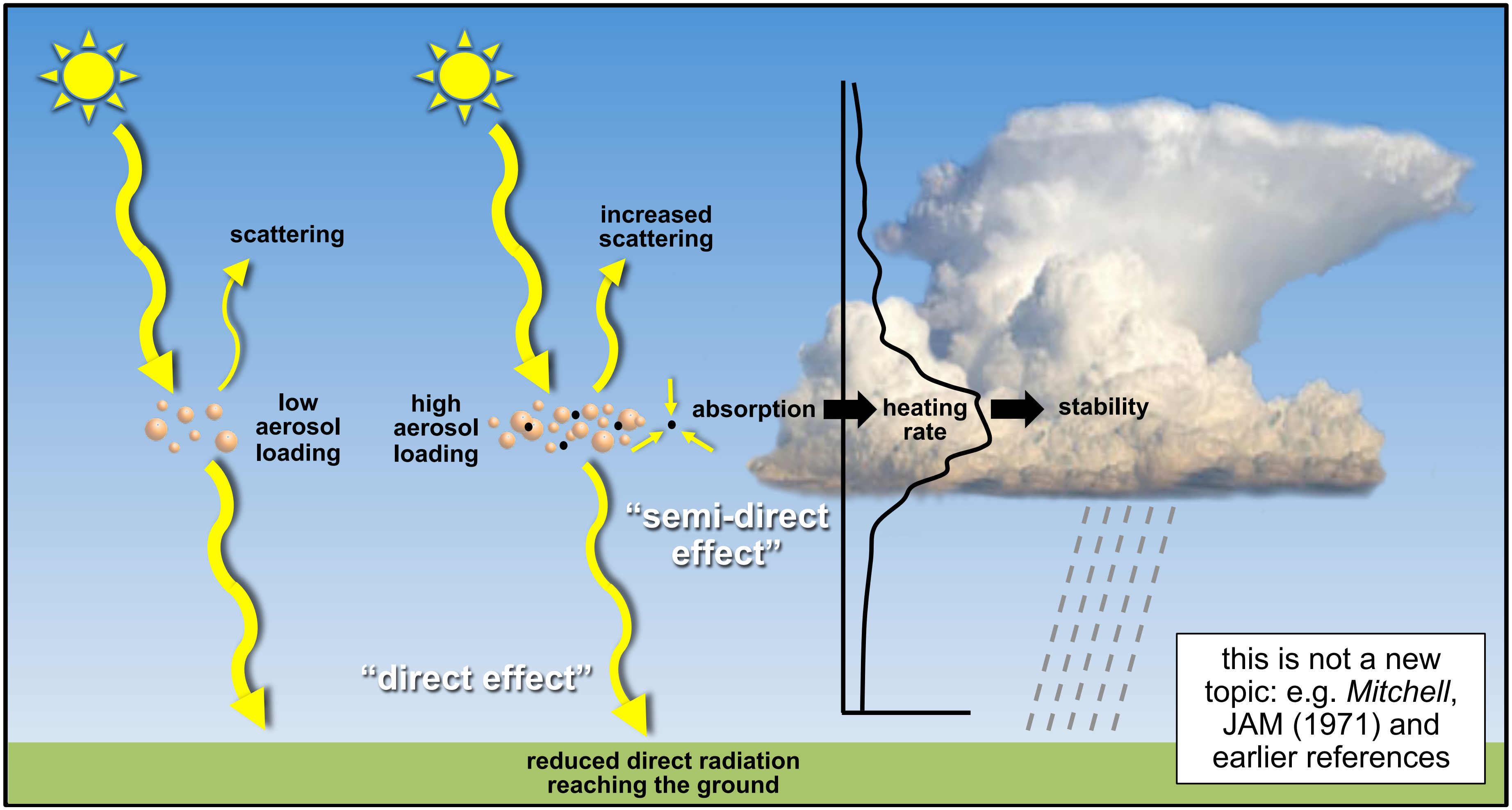
How Aerosols Affect Radiation and How Those Processes are Included in Atmospheric Models

Jerome Fast

14th Annual WRF User's Conference, June 24, Boulder, CO

Why Should We Care about Aerosols?



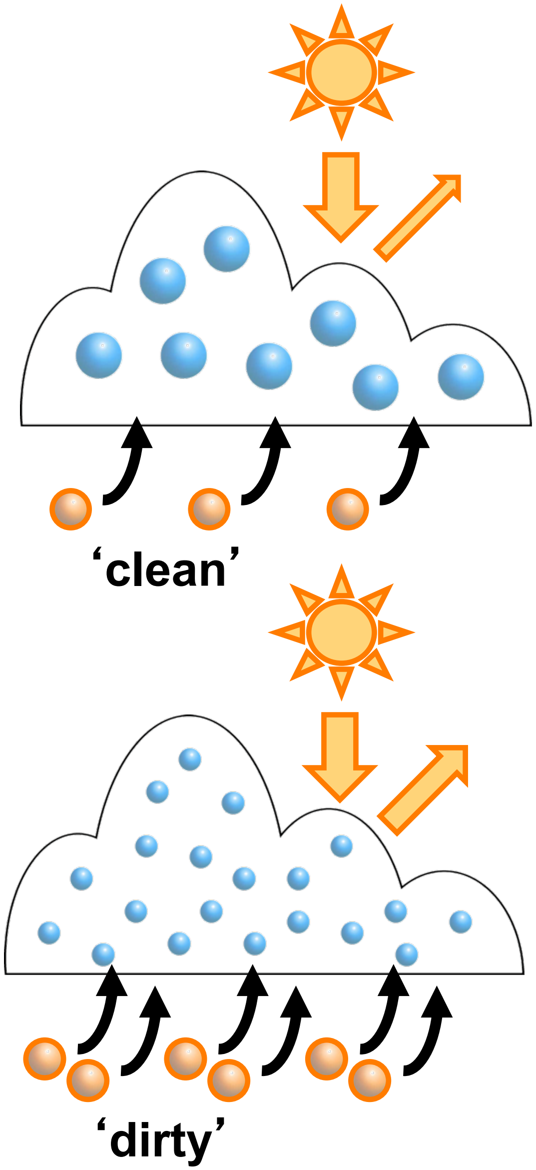
this is not a new topic: e.g. *Mitchell*, JAM (1971) and earlier references

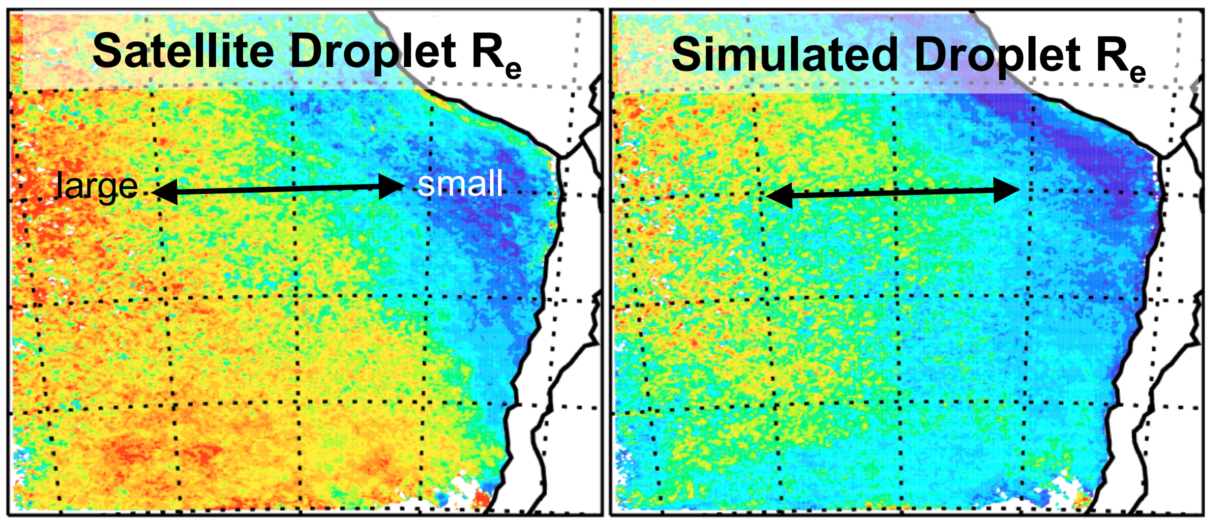
surface heat and latent heat fluxes → boundary layer temperature and moisture → clouds

while water vapor, carbon dioxide, ozone, and other trace gases affect the radiation budget, aerosols can also play a role

Indirect Effects of Aerosols on Radiation

- The number of activated aerosols affects the cloud drop size distribution, and consequently cloud albedo and radiation budget



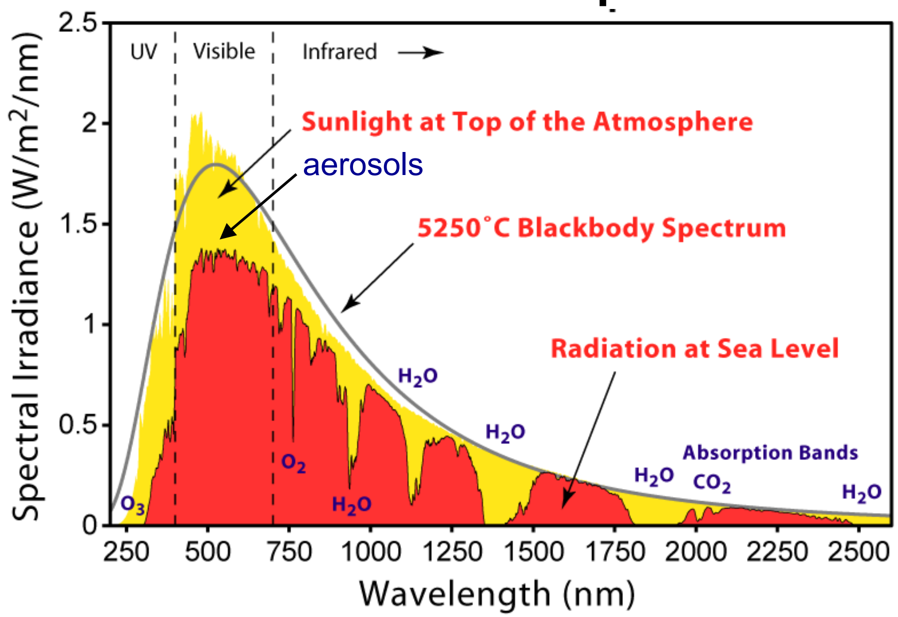


from *Yang et al.*, ACP (2011)

Aerosols in Relation to Radiation Modules

- Aerosols affect radiation mostly in the visible wavelength region
- In contrast with water vapor, carbon dioxide, and ozone, the temporal and spatial variability of aerosols is much larger and difficult to simulate
  - **Episodic Sources:** dust, biomass burning, volcanic (potentially large concentrations)
  - **"Continuous" Sources:** sea-salt, biogenic, anthropogenic (usually smaller concentrations)

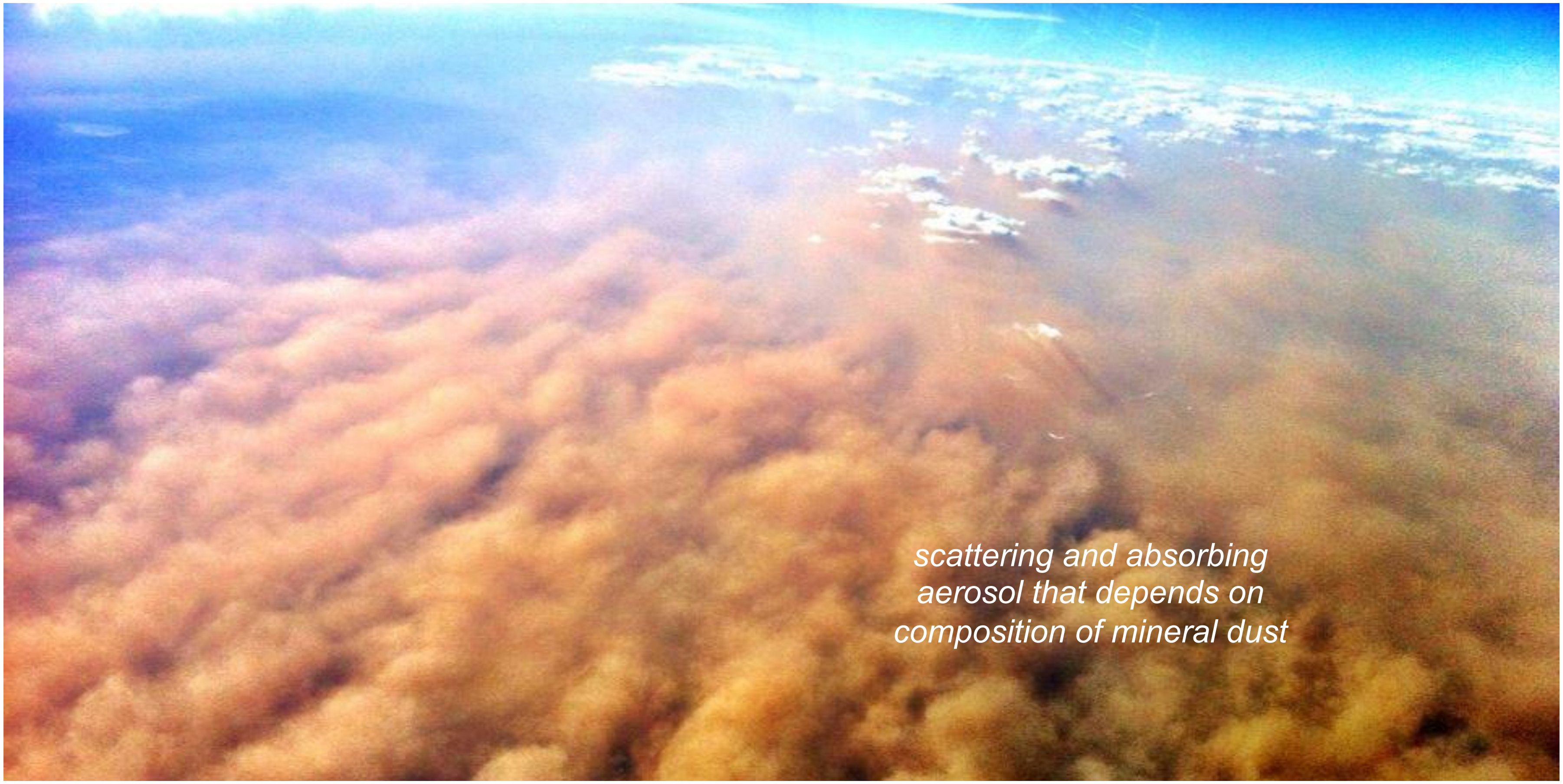
Solar Radiation Spectrum



How aerosol effects accounted for radiation modules in atmospheric models?

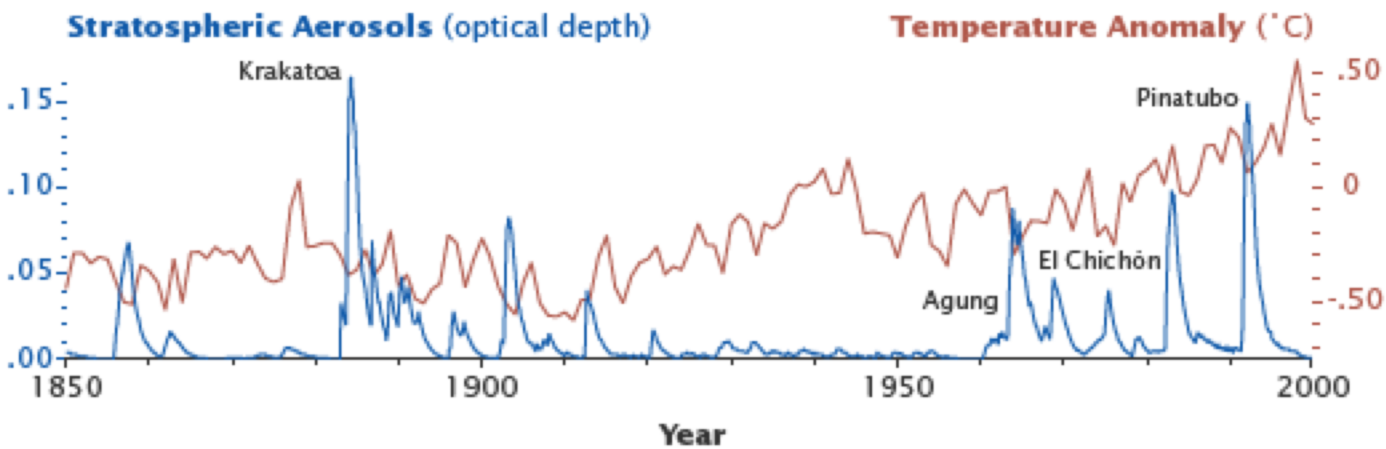
- Ignored - no effect of aerosols on radiation
- Use climatological aerosol properties – that may vary in space and seasonally
- Use prognostic aerosols (e.g. WRF-Chem)

Aerosol Source: Dust



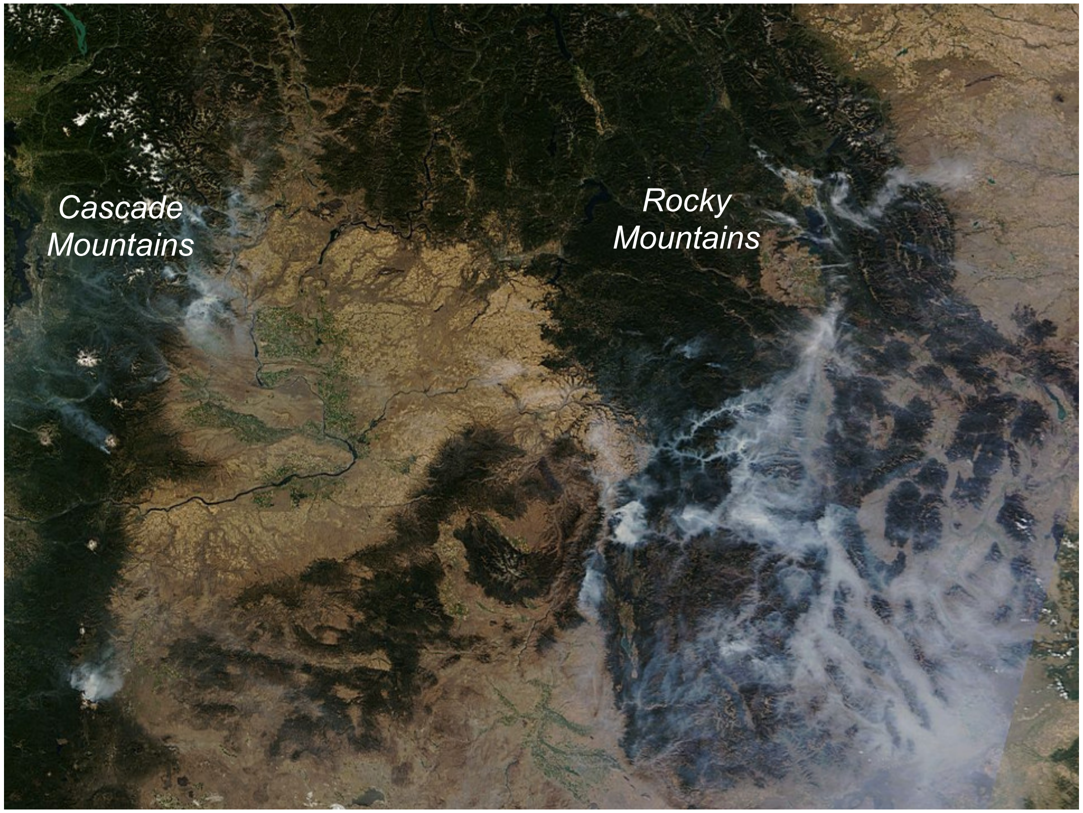
- Known source regions, e.g. Sahara and Gobi deserts
- Amount emitted depends on wind speed and soil moisture
- Seasonality of dust storms

Aerosol Source: Volcanic



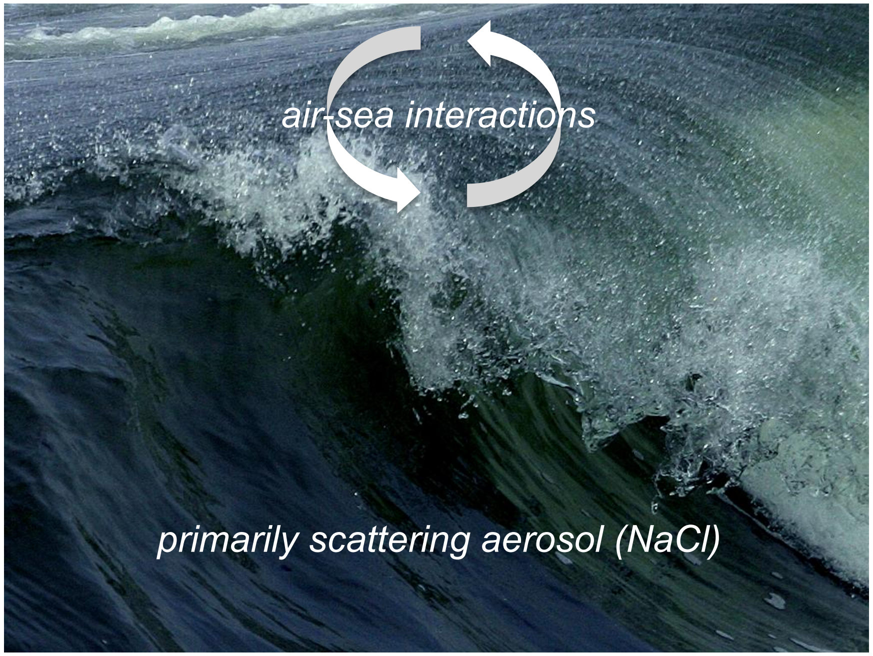
Aerosol Source: Biomass Burning

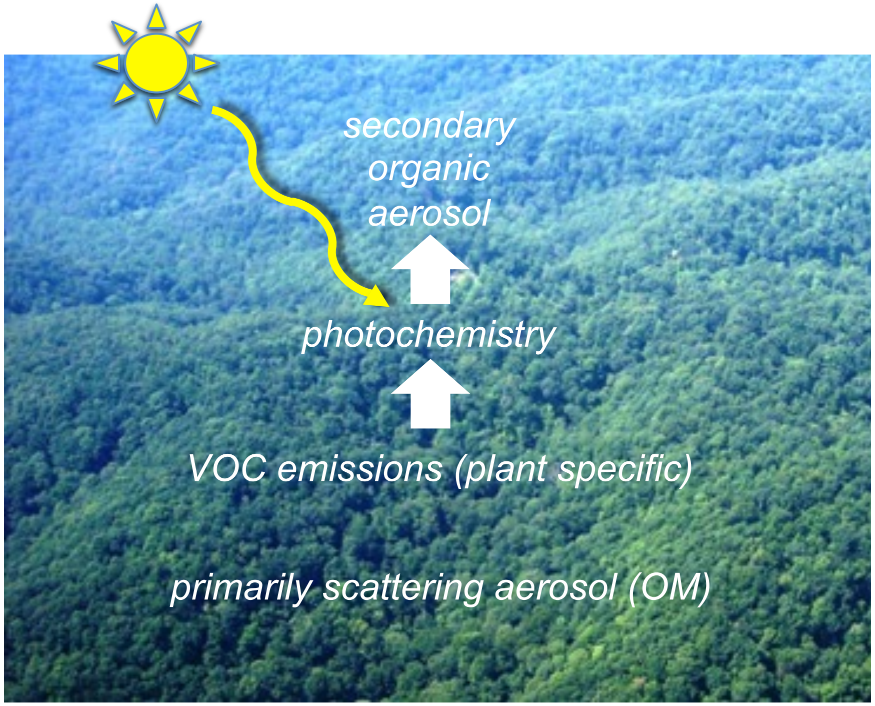
MODIS September 17, 2012



- Aerosol composition depends on vegetation type and phase of fire (smoldering vs flaming)
- Large persistent fires can significantly affect regional air quality
- Smoke often transported large distances, affecting radiation budget downwind

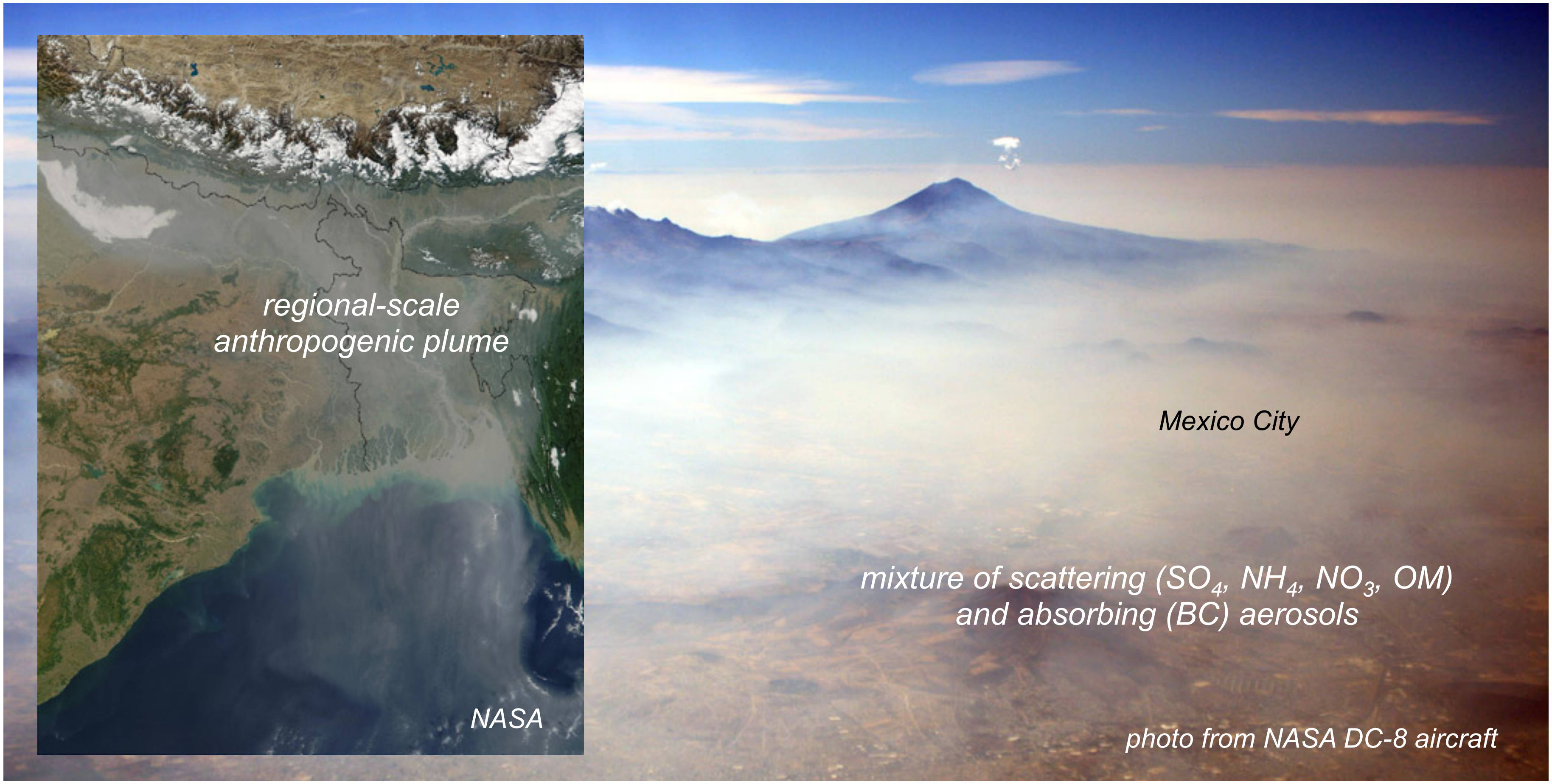
Aerosol Source: Sea Salt and Biogenic





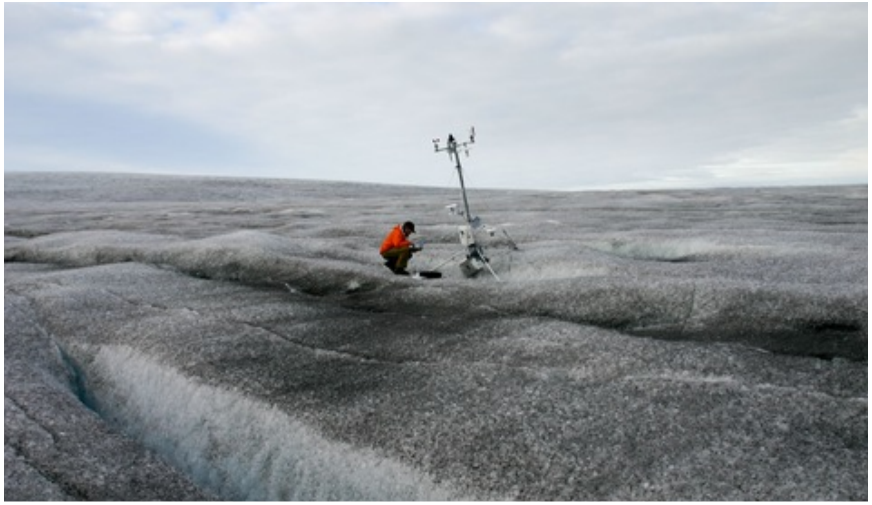
- Smaller concentrations than dust, volcanic, and biomass burning aerosols and therefore have a smaller overall effect on atmospheric radiation budget
- Sea-salt tends to be larger particles with shorter lifetimes
- Although concentrations of biogenic aerosols are usually low, it comprises a large fraction of the organics in the atmosphere globally

Aerosol Source: Anthropogenic

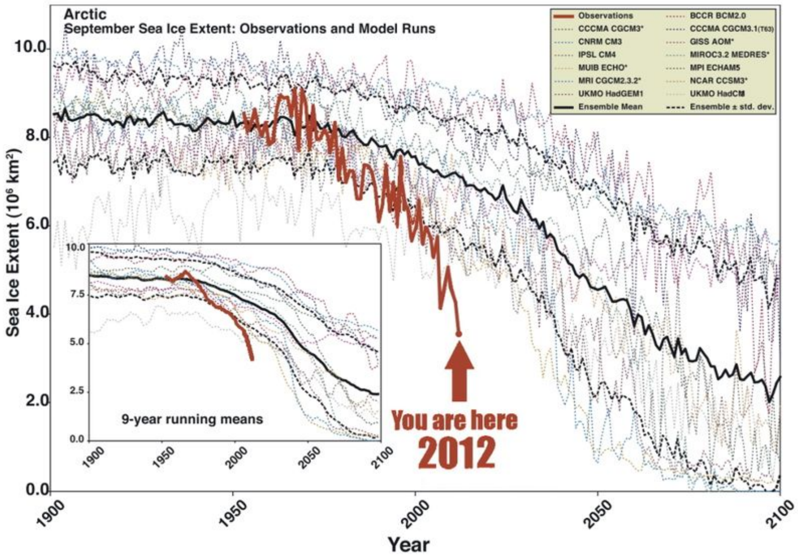


- Many sources including vehicles, industries, and residential
- Emissions of particulates and trace gas precursors are decreasing in some countries, but remain high in other countries

Effects of Soot and Dust on Snow

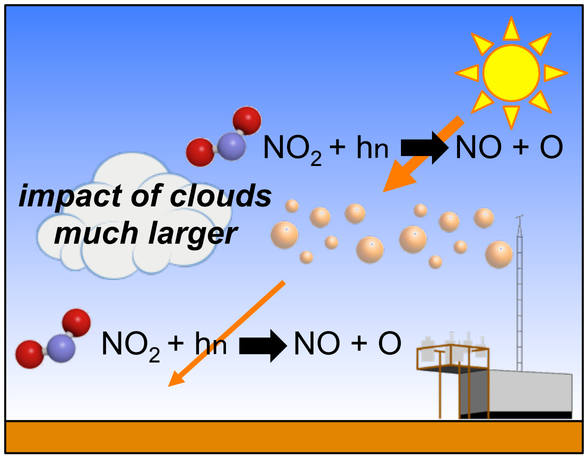


- Particulates deposited on snow change the surface albedo, so that more radiation is absorbed and less reflected
- Enhances melting of snow and ice
- Global models do not represent the rapid decrease in sea ice extent – do aerosol radiative effects represented in models contribute to this error?

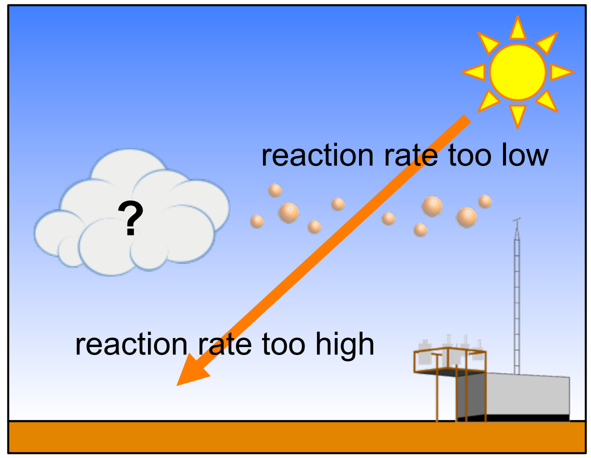


Effects on Photochemistry

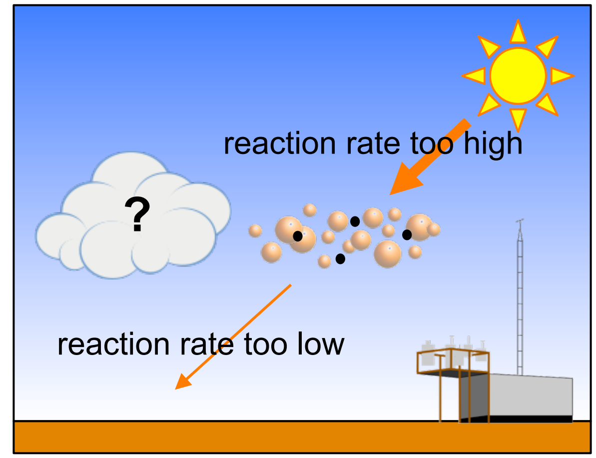
Observed Aerosols

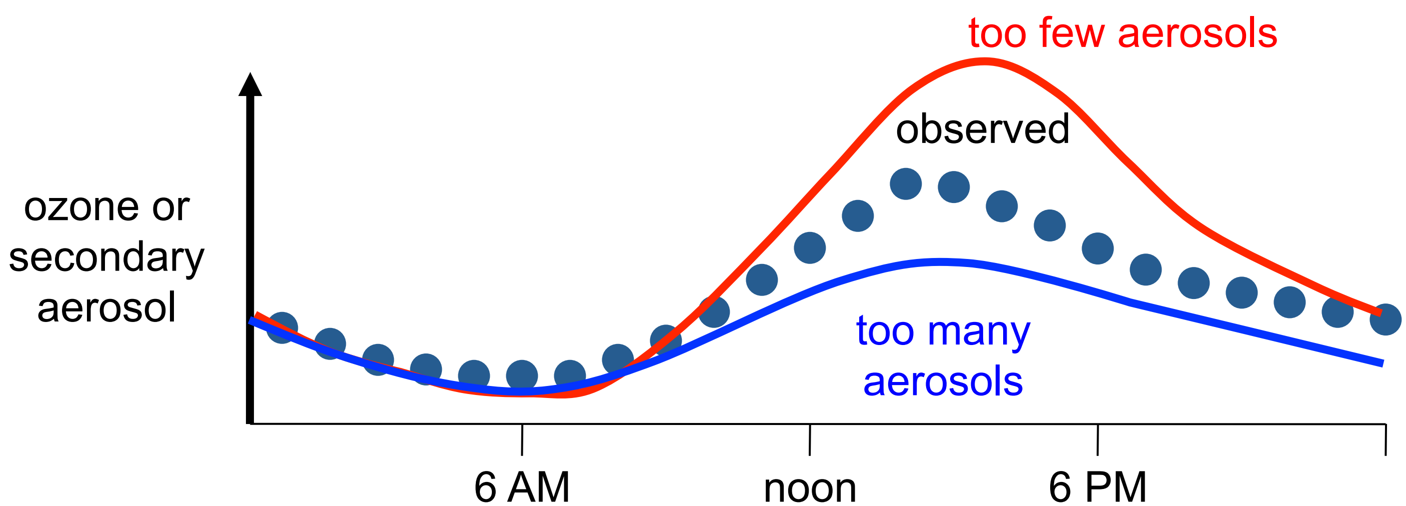


Simulated:
Too Few or Too Thin



Simulated:
Too Many or Too Thick



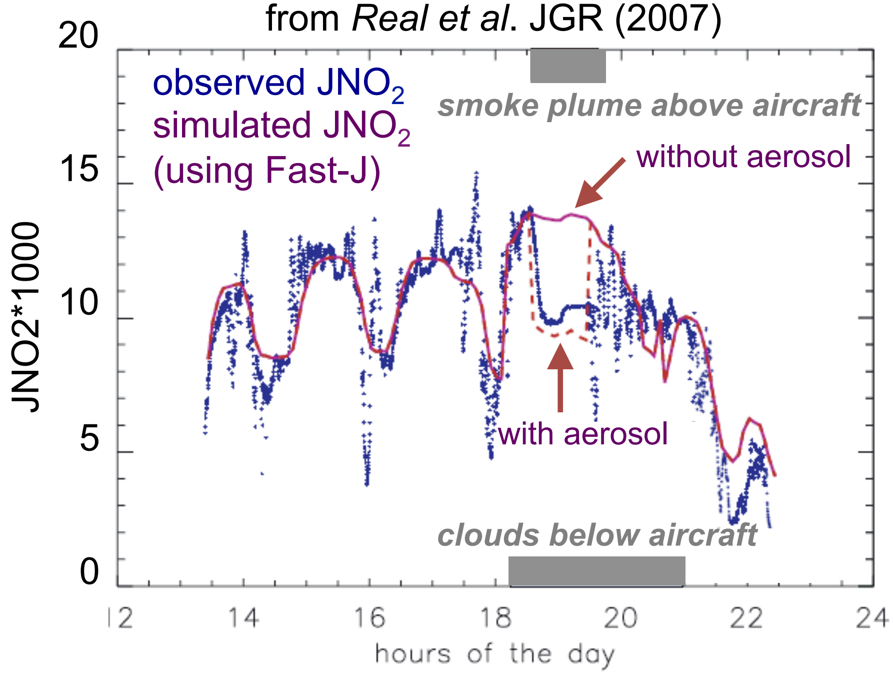


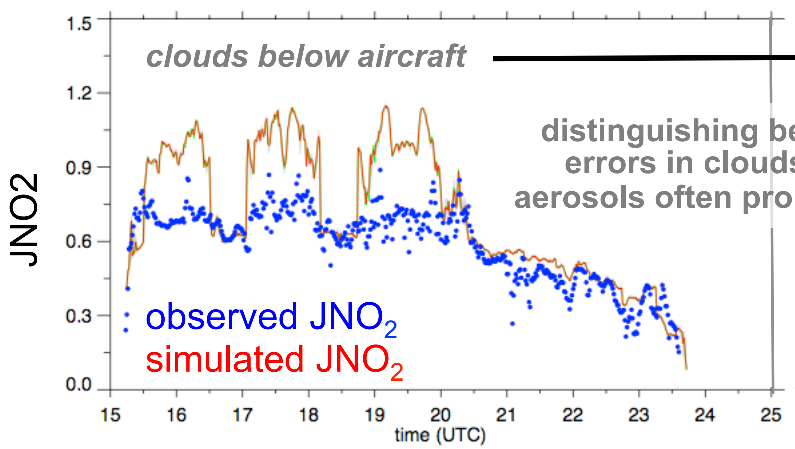
errors could impact simulated concentrations the next day

Photochemistry: Examples

Impact of Aerosols on JNO_2

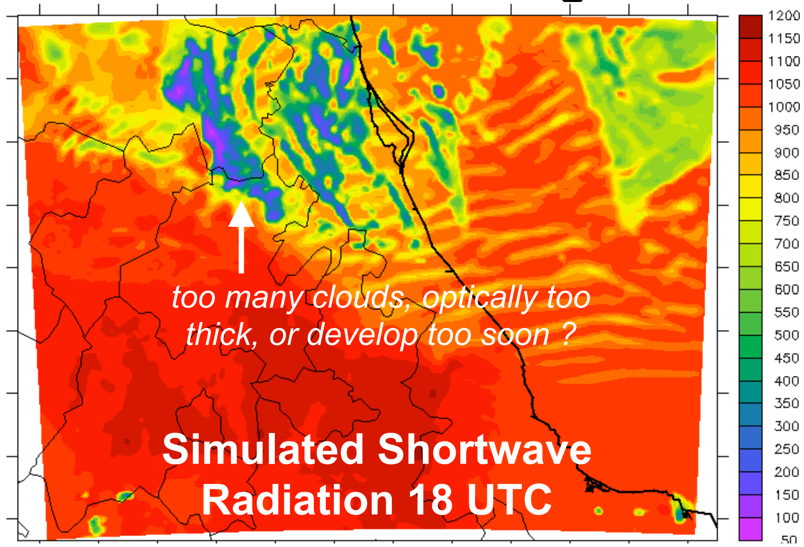
from *Real et al*. JGR (2007)

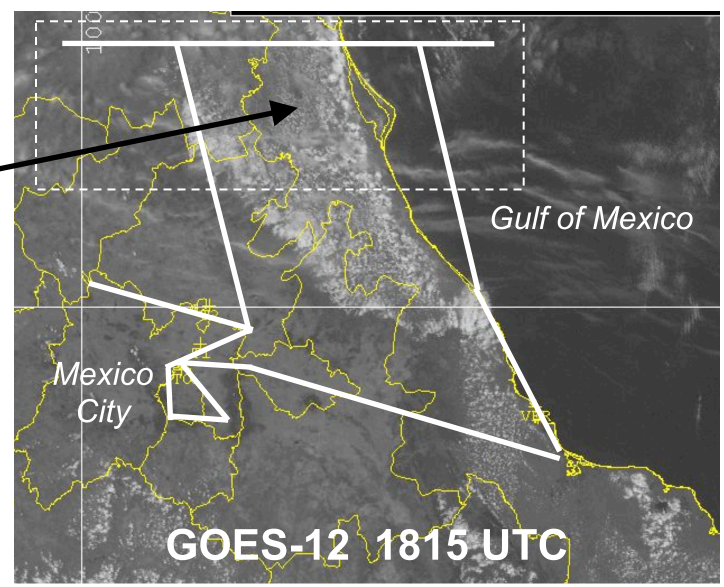




distinguishing between errors in clouds and aerosols often problematic

MILAGRO C-130 Flight





Terminology:
Parameters used by Measurements and Model Formulations

Aerosol Optical Depth, t_l

- **Extinction coefficient**: fractional depletion of radiance per unit path length (km^{-1}) due to scattering and absorption by aerosols
- **Aerosol optical depth** (AOD) or **thickness** (AOT): integrated extinction coefficient over a vertical column, $I / Io = e^{-t}$
  - AOD = 0 no aerosol effect
  - AOD ~ 1 "large"
  - AOD > 1 extremely high aerosol concentrations

AOD: Global Aerosol Seasonality

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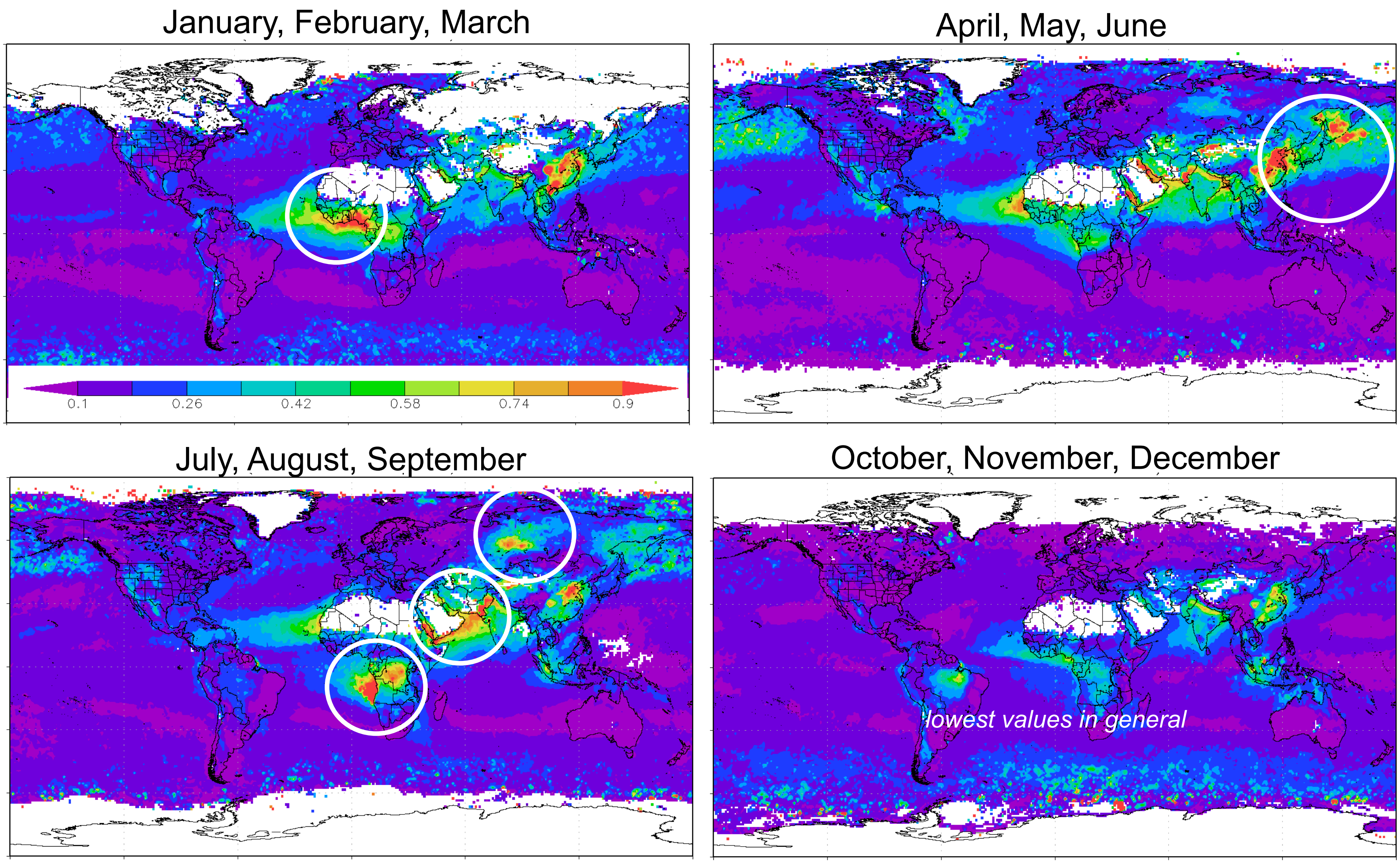
Average AOD from MODIS Terra



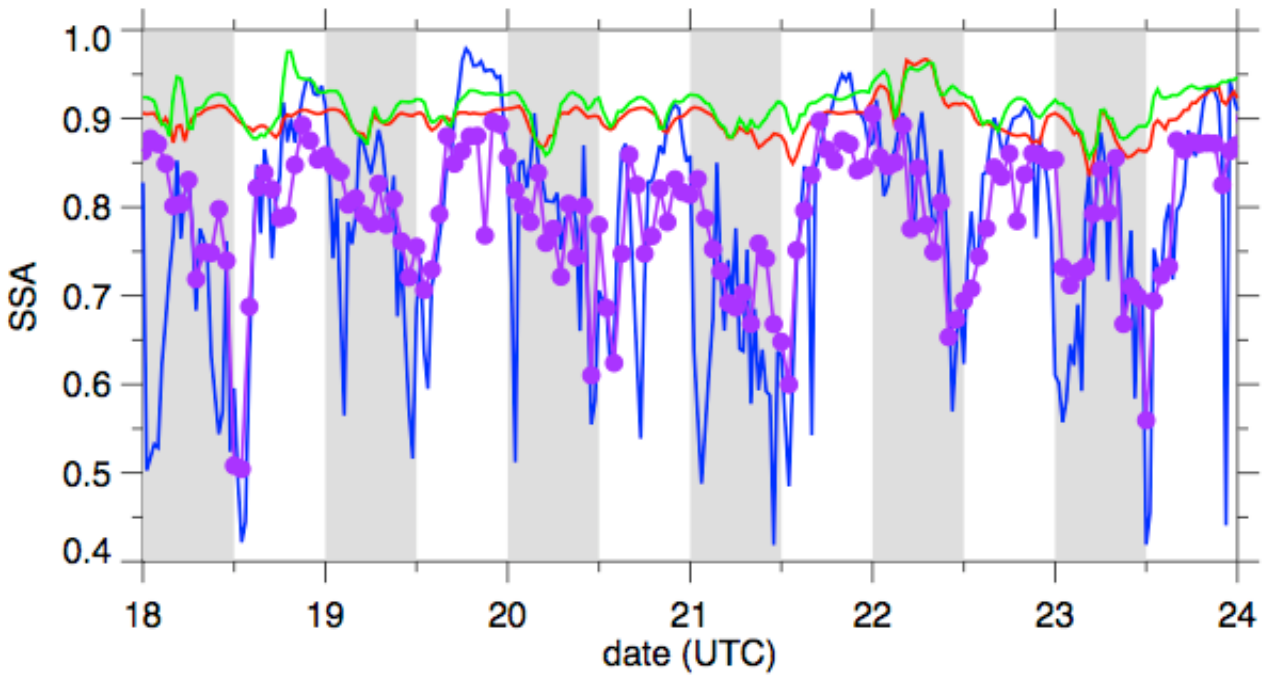
Single Scattering Albedo, w_o

- SSA is ratio of scattering efficiency to to extinction efficiency, $w_o = k_s / (k_a + k_s)$
  - SSA = 1 all particle extinction due to scattering
  - SSA = 0 all particle extinction due to absorption

can measured these

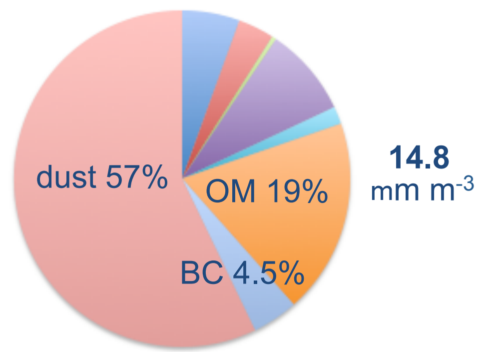
- Models simulate t_l "reasonably well", but there are large uncertainties in w_o

SSA_{870nm} near Mexico City

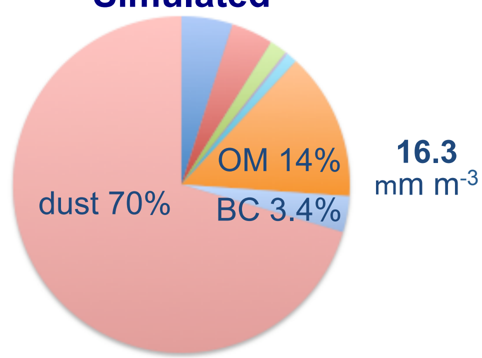


aerosol optical properties driven by measurements

Observed 12 UTC March 20

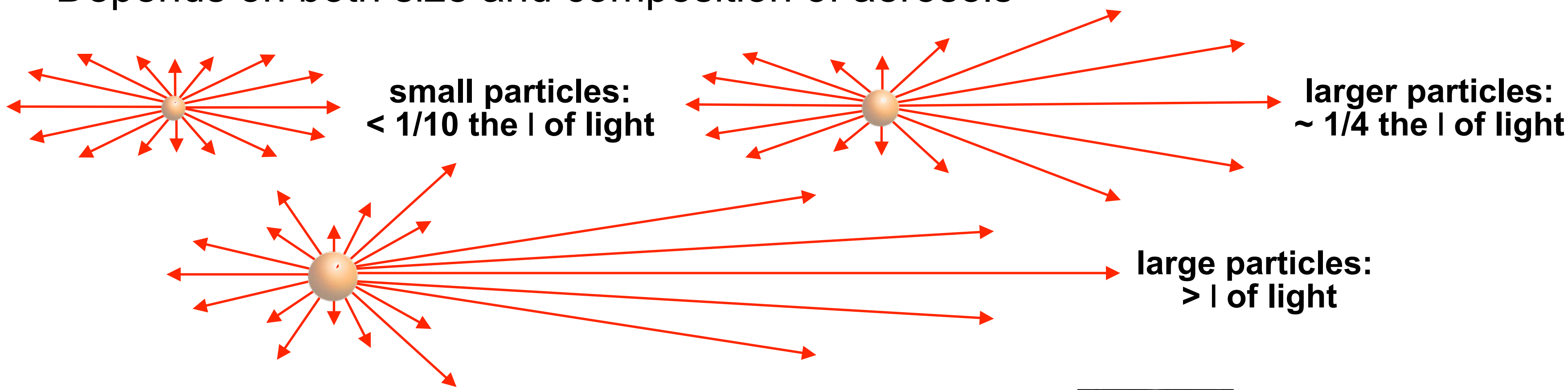


Simulated

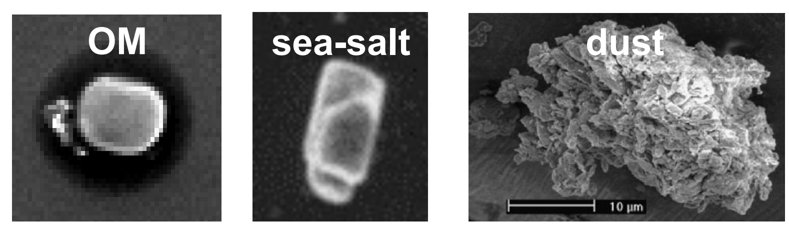


Asymmetry Factor, g

- Preferred scattering direction (forward or backward) for the light encountering the aerosol particles
  - Approaches 1 for scattering strongly peaked in the forward direction
  - Approaches -1 for scattering strongly peaked in the backward direction
  - g = 0 means scattering evenly distributed between forward and backward scattering (isotropic scattering – such as from small particles)
- Depends on both size and composition of aerosols



- Theoretical relationships used to derive g from measurements



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How Aerosol Effects on Radiation Included in Atmospheric Models?

Overall Methodology for Prognostic Aerosols

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Generic Aerosol Optical Property Module

size and number distribution
composition
aerosol water
→
refractive indices → Mie theory → layer optical depth, t_l
single scattering albedo, w_o
asymmetry factor, g
→
shortwave / longwave radiation

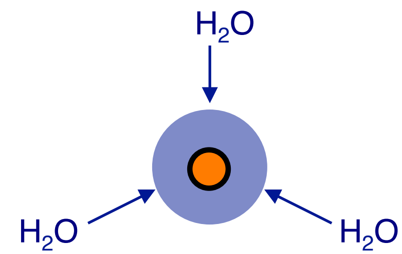
- τ, ω_o, and g computed at 300, 400, 600, and 1000 nm for shortwave radiation
- As of v3.3, τ, ω_o, and g computed at 16 wavelengths for longwave radiation

Angstrom exponent used to convert to wavelengths needed by radiation schemes

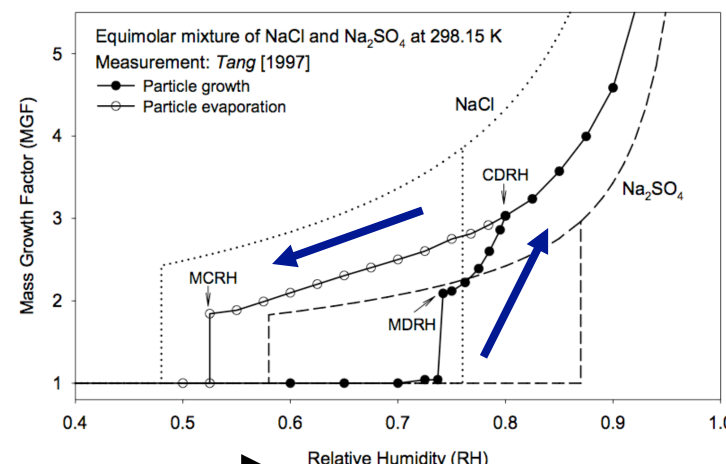
- Compatible with GOCART, MADE/SORGAM, MOSAIC, and MAM aerosol models as of v3.5
- Compatible with Goddard shortwave scheme and RRTMG shortwave and longwave schemes

Importance of Aerosol Water

- Aerosol water will have a big impact on optical properties



- Aerosol water depends on relative humidity (RH); thus predictions of RH need to be examined when evaluating aerosol direct radiative effects
- Composition affects water uptake: hydrophobic vs hydrophillic aerosols
- Aerosols models have different methods of computing aerosol water
  - **GOCART:** Petters and Kreidenweiss (2007)
  - **MADE/SORGAM:** diagnosed
  - **MOSAIC:** prognostic species that accounts for hysteresis effect



Refractive Indices

- Refractive index of a substance is a dimensionless number that describes how light propagates through a medium
- Refractive indices in models based on literature values derived from laboratory experiments, vary with wavelength for some aerosol compositions

Default Values for SW Radiation in WRF (users can change)

	real part		imaginary part
BC =	1.850	+	0.71i (all l)
OM =	1.450	+	0.00i (all l)
SO_4 =	1.468	+	1.0e-9i (300 nm), small l dependence
NH_4NO_3 =	1.500	+	0.00i (all l)
NaCl =	1.510	+	0.866e-6i (300 nm), small l dependence
dust =	1.550	+	0.003i (all l), depends on type of dust
H_20 =	1.350	+	1.52e-8i (300 nm), small l dependence

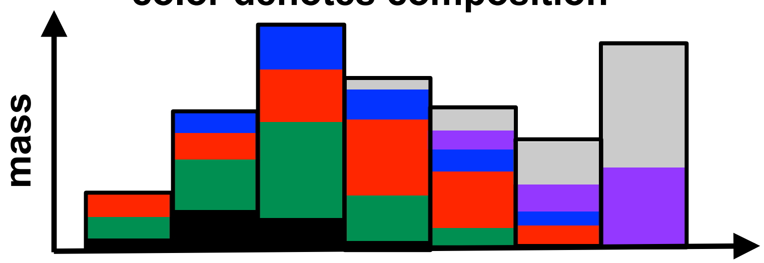
greater the # $\rightarrow$ more absorption

similar relationships for LW radiation

- On-going research:
  - secondary organic aerosols (SOA) may be absorbing at near-UV range
  - “brown carbon”

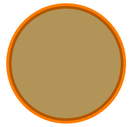
Mixing Rules for Mie Calculations

Prior to the Mie calculations, refractive indices need to be averaged among the compositions in some way for discrete size ranges of the aerosol size distribution. All particles within a size range assumed to have the same composition, although relative fraction can differ among size ranges.

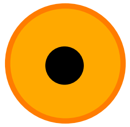


Currently three choices in WRF:

- **Volume Averaging:** averaging of refractive indices based on composition



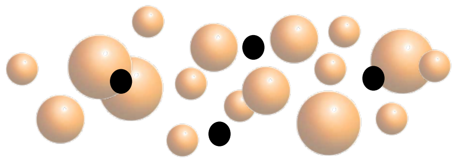
- **Shell-Core**: black carbon core and average of other compositions in shell (Ackermann and Toon, 1983; Borhren and Huffman, 1983)



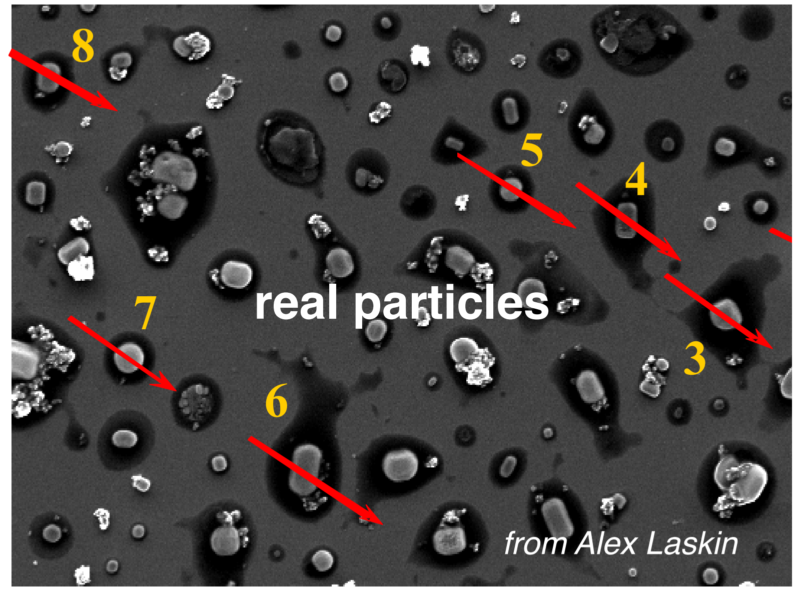
- **Maxwell-Garnett:** small spherical randomly distributed black carbon cores in particle (Borhren and Huffman, 1983)

Mie Calculations

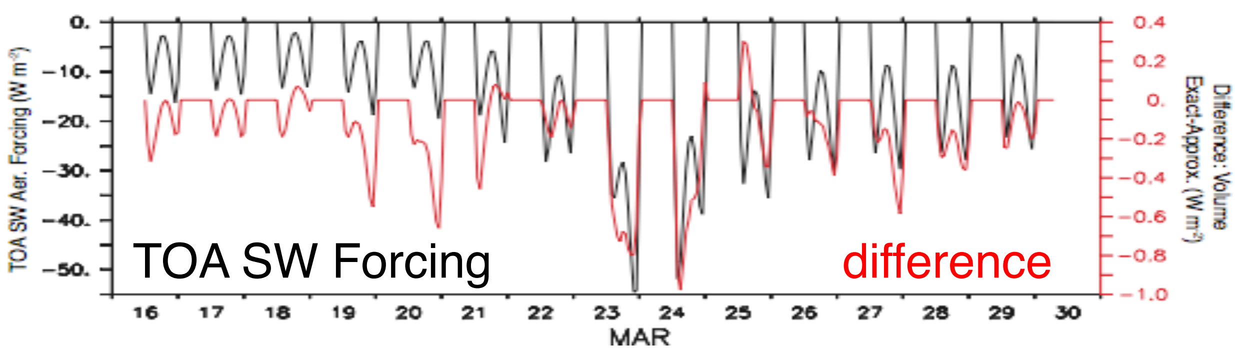
- The Mie solution to Maxwell's equations describes the scattering of radiation by a sphere, used to obtain t_l, w_o, and g



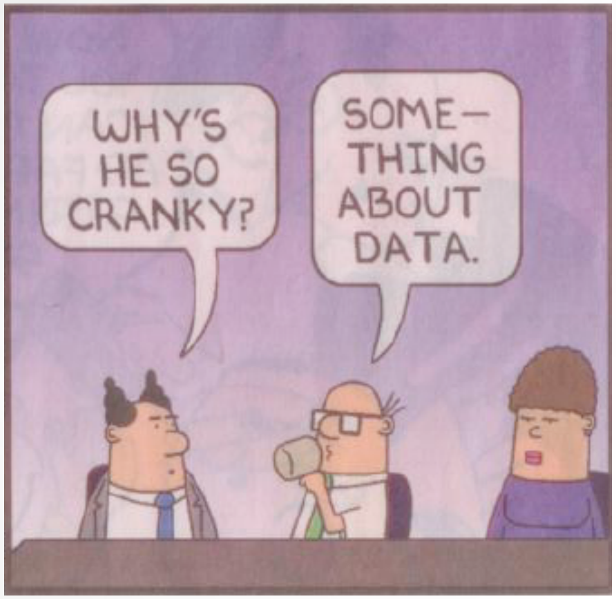
- Aerosols are rarely spheres; however, aged aerosols become more "sphere-like"
- Several "standard" codes available and one is included in WRF
- Mie codes can be computationally expensive, so an approximate version (*Ghan et al*. JGR, 2001) is also available



other codes available to handle more complex morphology, but not clear if it is really necessary

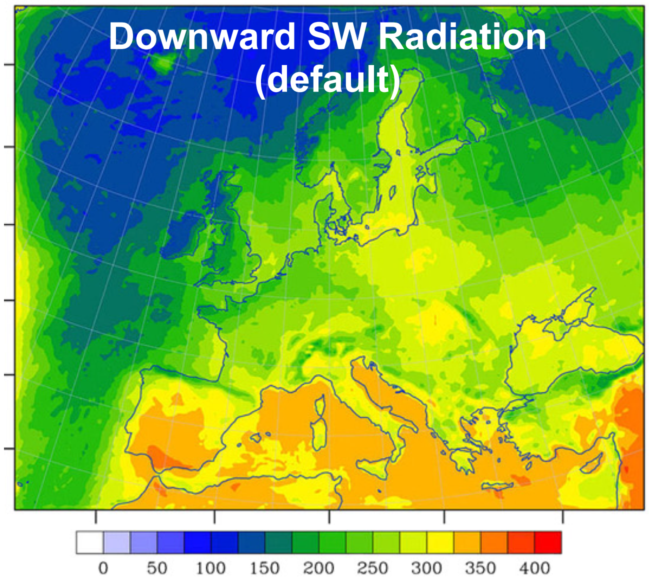


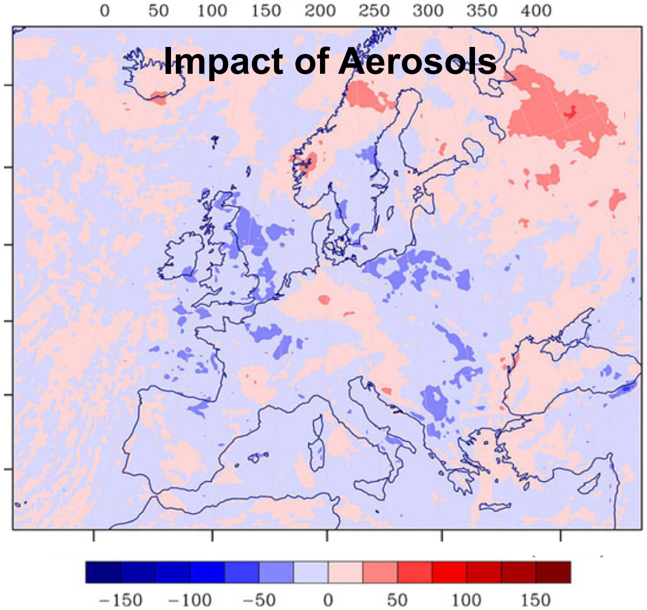
Examples: Impacts and Evaluation of Optical Properties

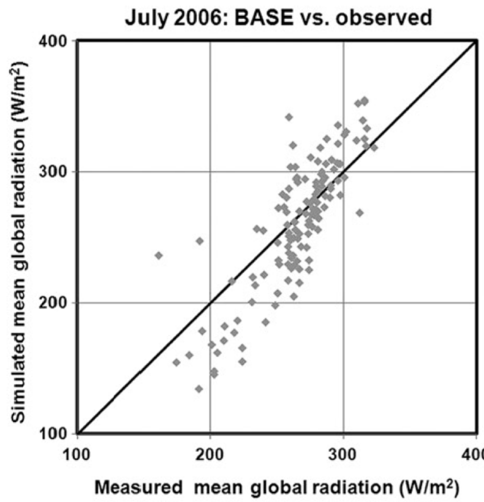


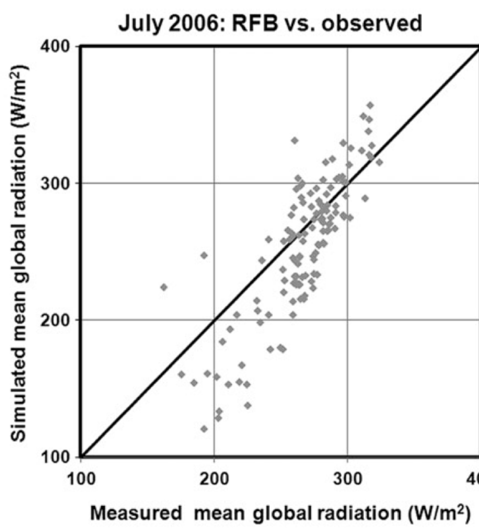
Impact of Aerosols over Europe

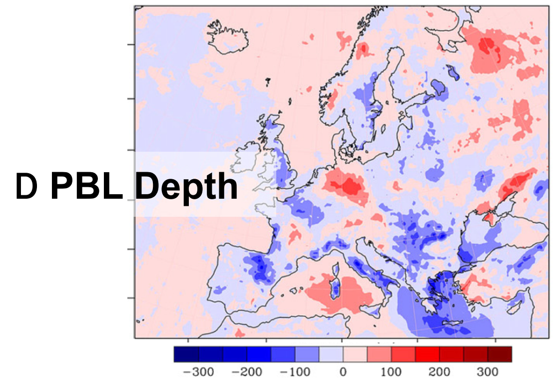
from *Forkel et al.* ACP (2012)

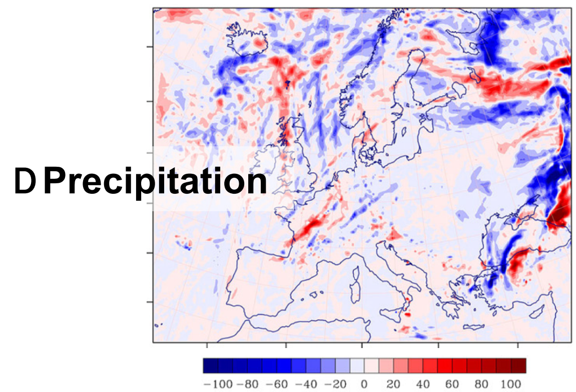


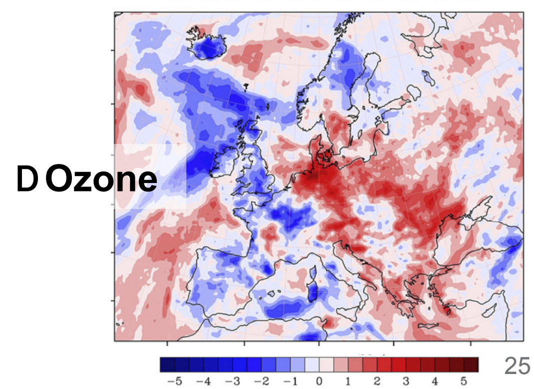






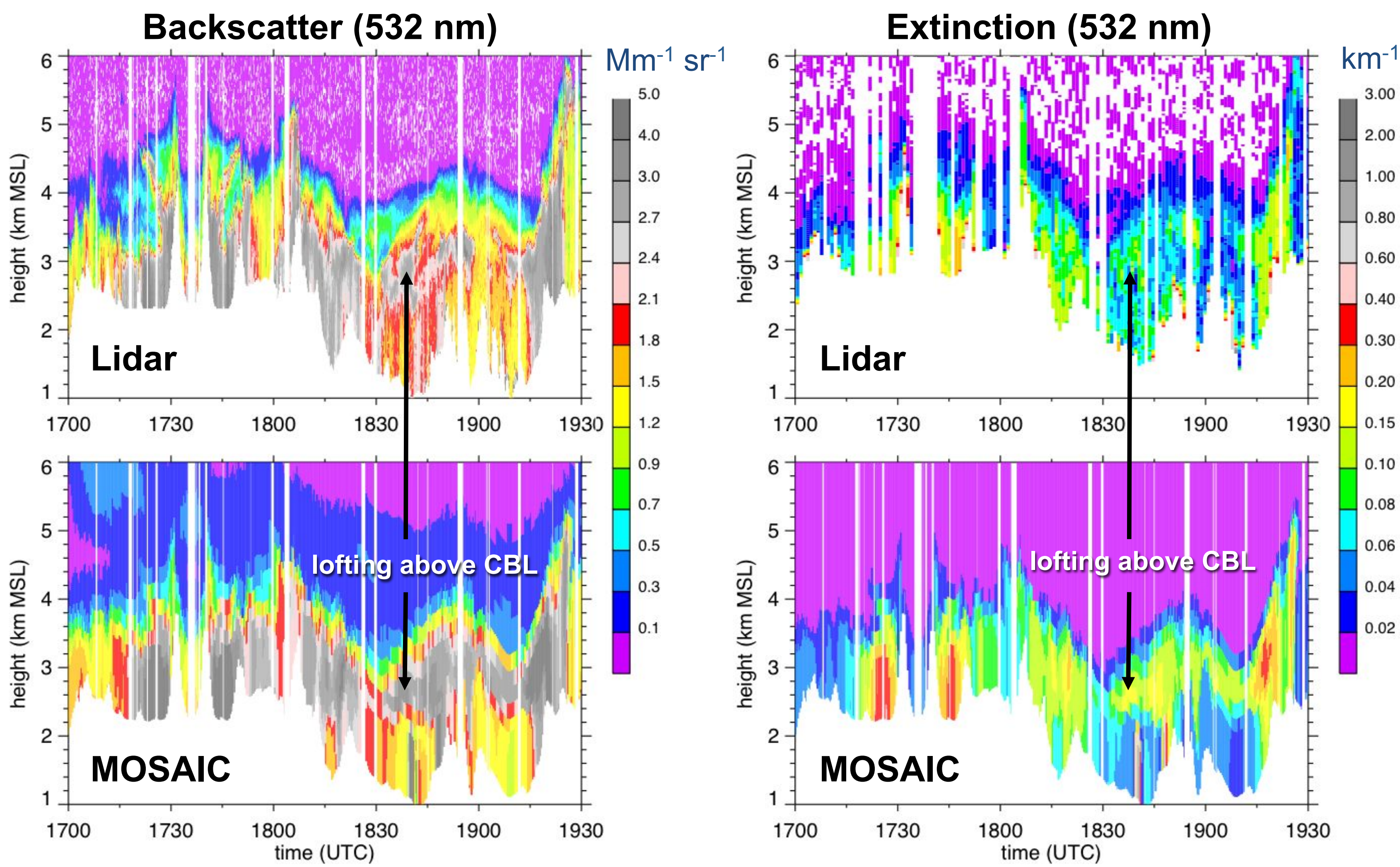






Extinction Profiles over Central Mexico
from *Fast et al.* ACP (2009)

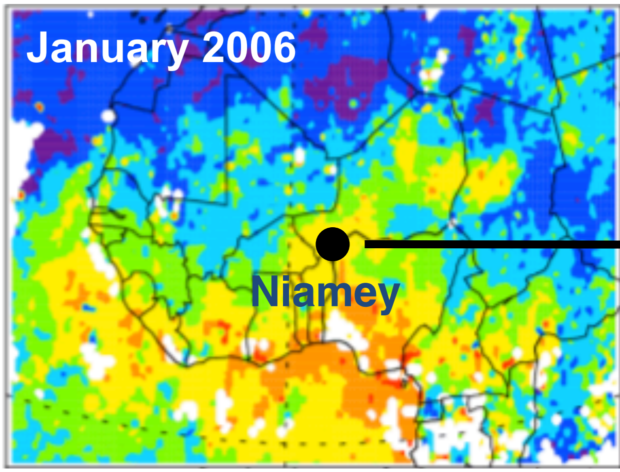
NASA B-200 Aircraft Flight Path 13 March 2006 during MILAGRO



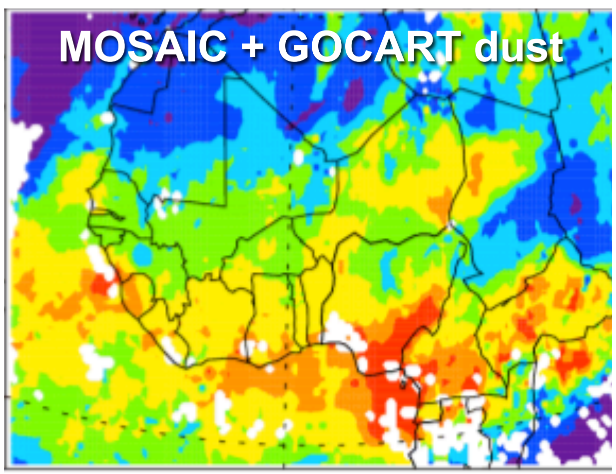
Dust and Biomass Burning in Africa

from *Zhao et al.* ACP (2010)

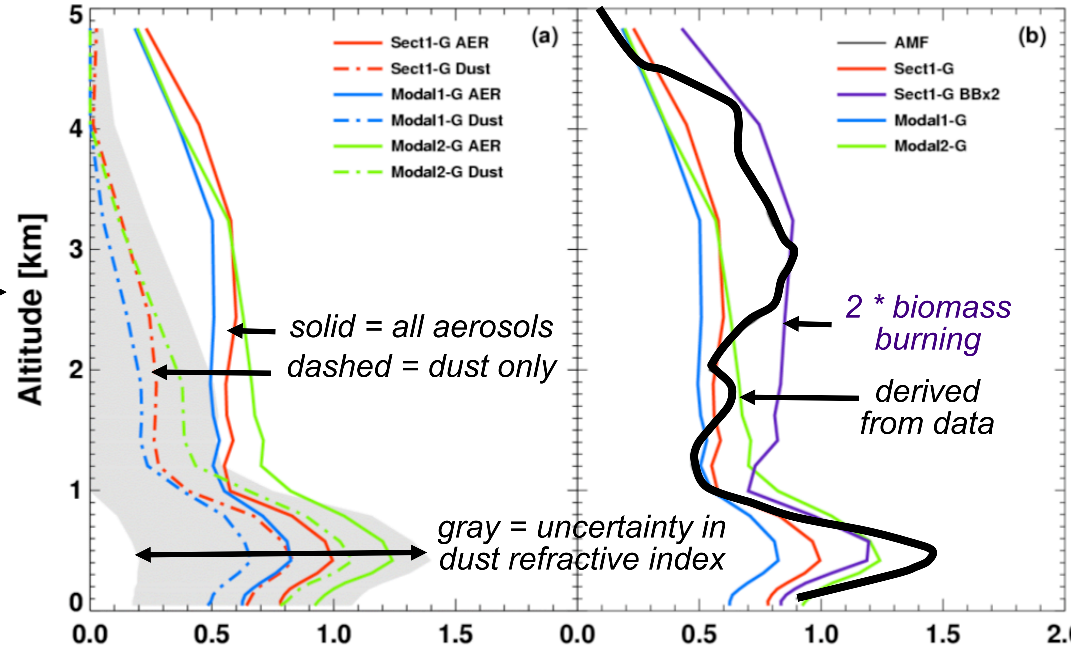
Averaged Terra-MISR AOD

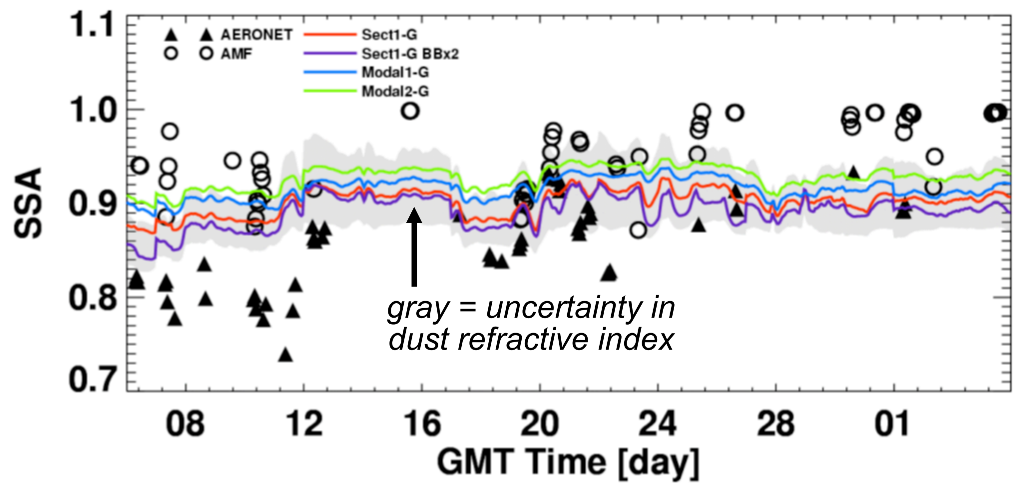


Simulated AOD



SW Radiative Heating Rate Profile (K day^{-1})





Two Column Aerosol Project (TCAP)

Providing Detailed Measurements for Closure Studies

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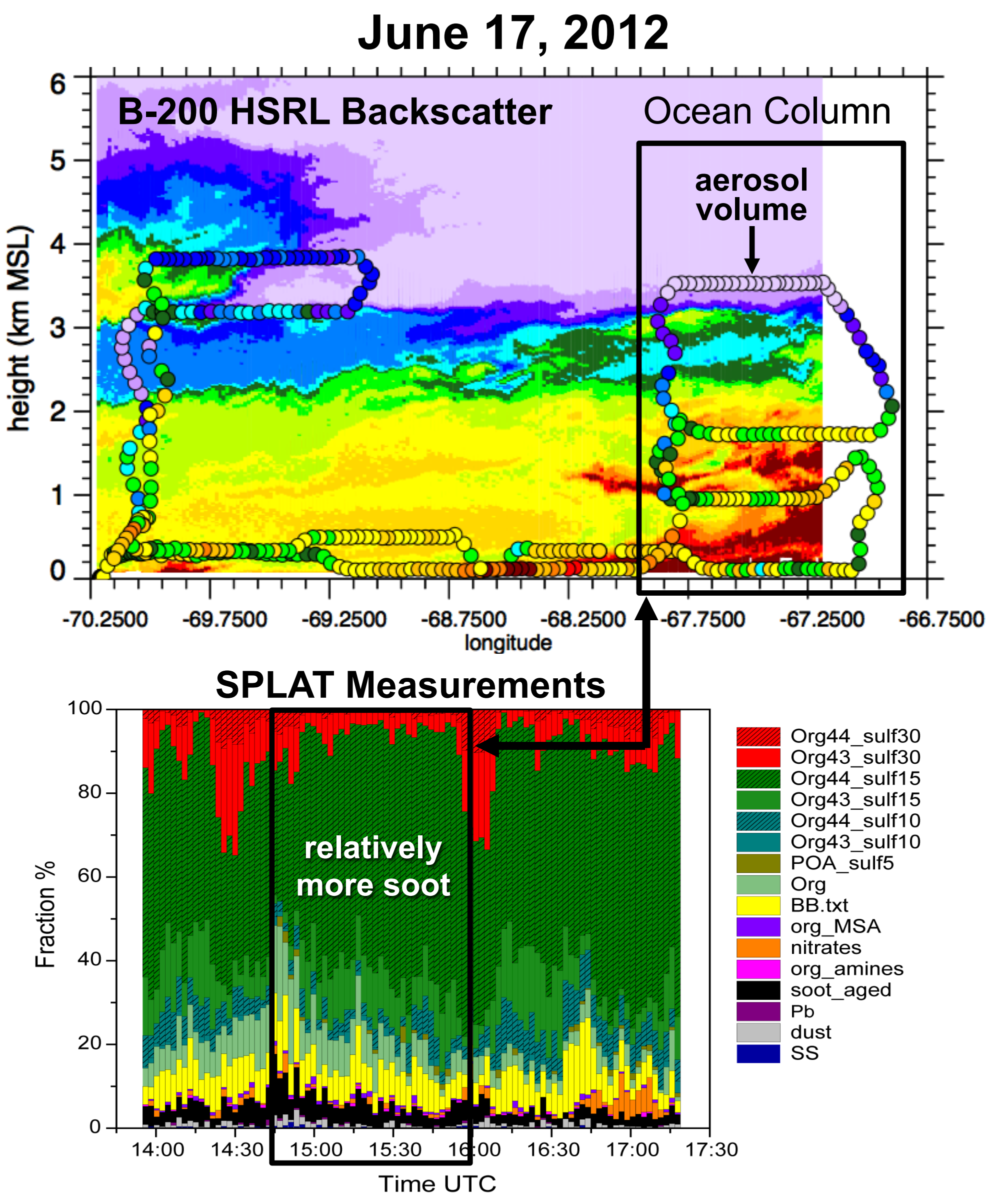
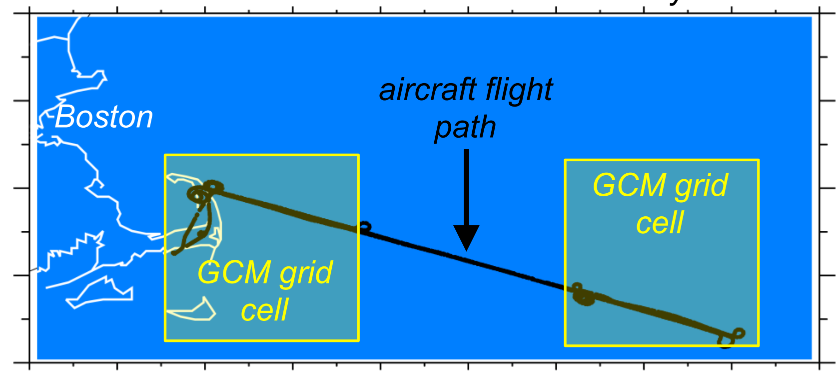


TCAP led by PNNL and supported by DOE ARM Climate Research Facility

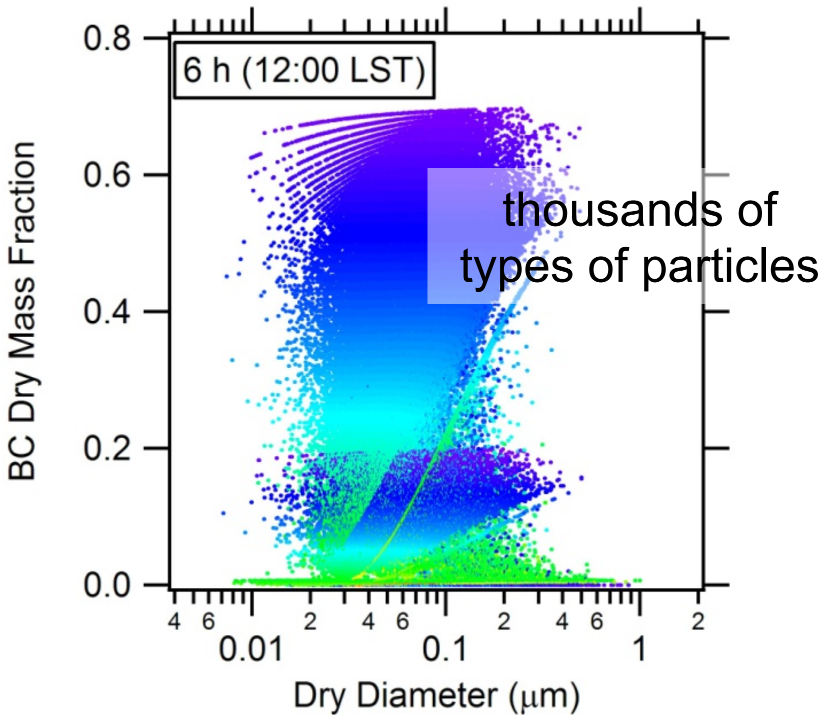


- TCAP collected measurements of aerosol size, composition, and mixing state as well as optical properties from in situ and remote sensing instruments
- **Column Closure Studies:** Aerosol microphysical properties will be used as input to optical property modules to identify uncertainties in simulated scattering, absorption, and extinction associated with model assumptions

Alternative Treatments of Mixing State

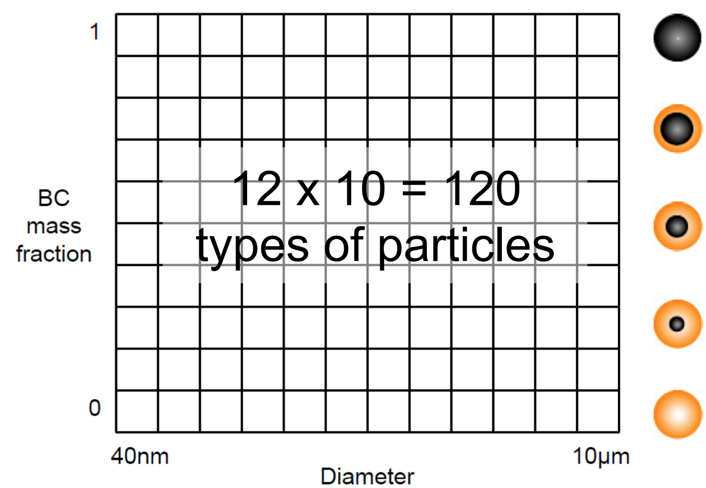
There are more complex treatments of mixing state being tested

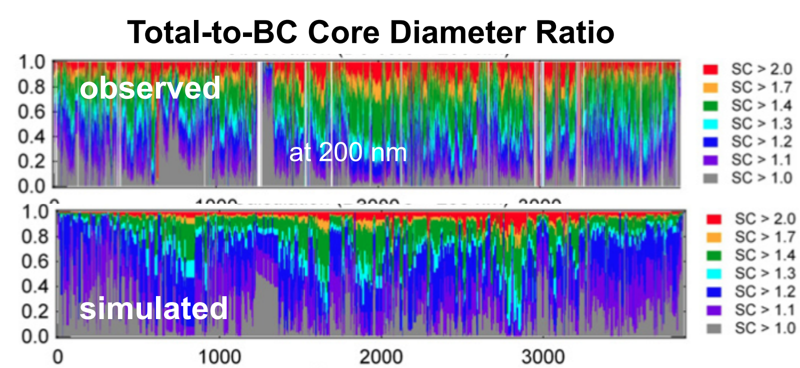
- Explicitly simulate each individual particle (e.g. PartMC-MOSAIC, *Zaveri et al*., JGR, 2010)



treatment of mixing state affects impact of aerosols in radiation

- Sectional approach to represent black carbon mixing state (e.g. *Matsui et al.* JGR, 1013)



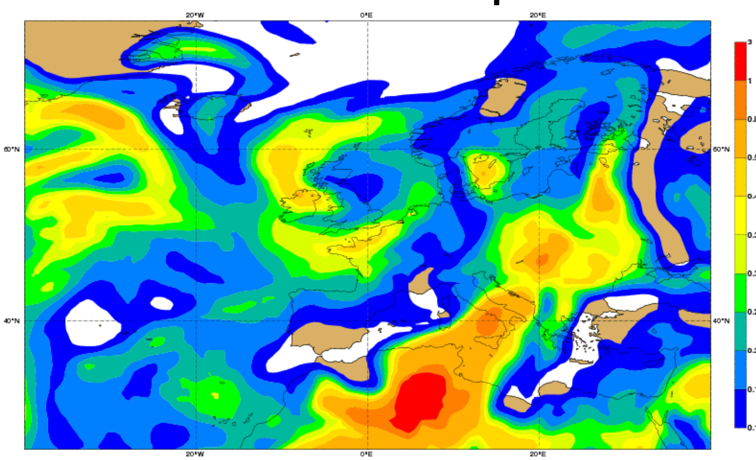


Is it Important to Include Aerosol Effects?

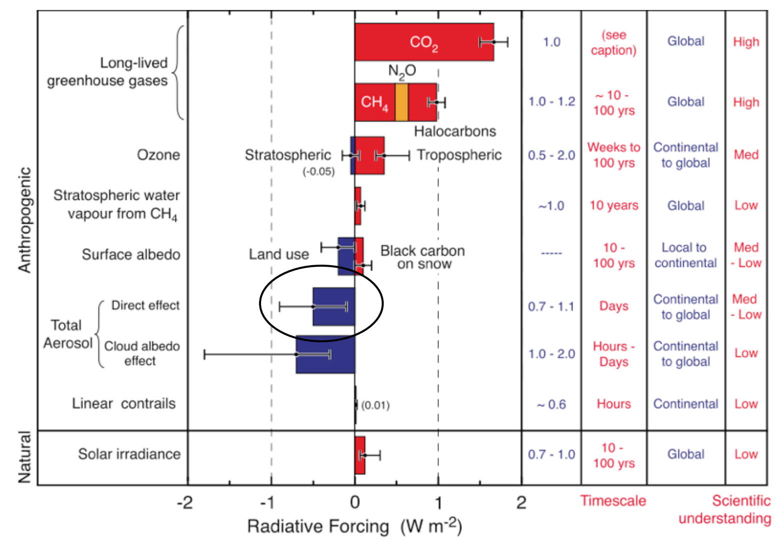
Depends on Your Application and Science Objectives

- **Weather Forecasting:**
  Debatable. While including feedbacks associated with aerosol-radiation interactions is more realistic, there is little evidence to show that its inclusion statistically improves forecast skill for meteorological and chemical quantities. Important for periods of extremely high aerosols?
- **Climate Simulations:**
  Yes. Average effect important to include. Aerosols lead to a net cooling of the atmosphere, although there is still some uncertainty
- Need to consider whether prescribed aerosols are sufficient or if prognostic aerosols are needed

AOD Forecast over Europe - MACC



from IPCC Report



Questions?

Acknowledgements: This work is supported by DOE's Atmospheric System Research (ASR) program. I thank my team: Bill Gustafson, Richard Easter, Rahul Zaveri, Chun Zhao, Balwinder Singh, as well as Georg Grell and Steven Peckham for their contributions