Aerosols and Their Climate Impacts in AM3/CM3

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Outline of this lecture

1. **Fundamentals of the interactions between aerosols and climate;**
2. **Treatment of aerosol effects in AM3/CM3;**
3. **An example of CM3-facilitated science.**

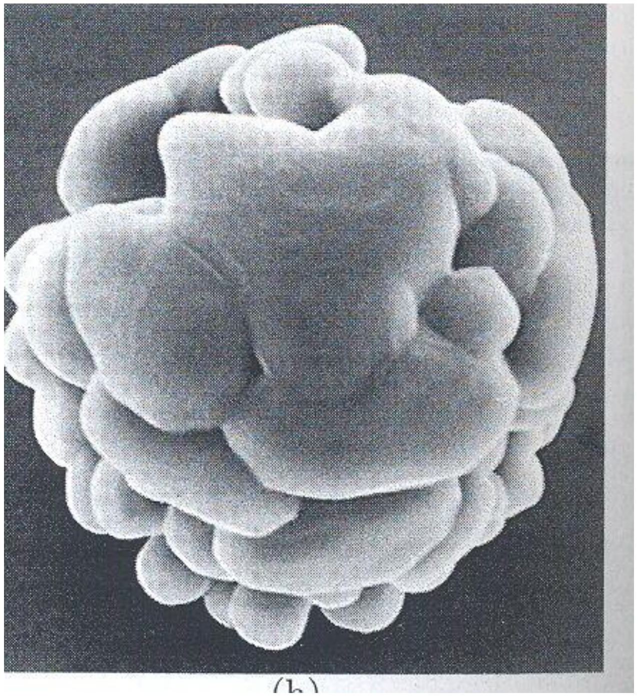
Part 1: Fundamentals

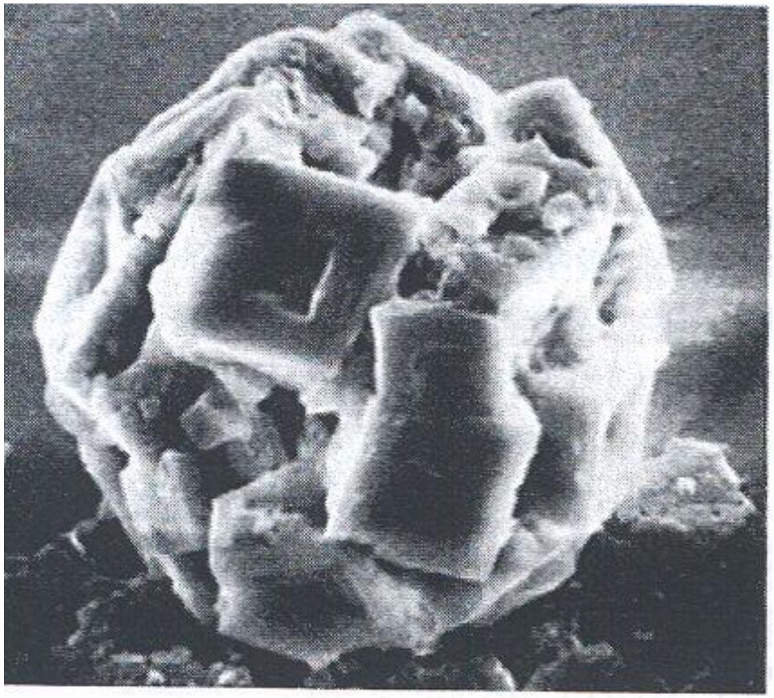
What are aerosols?

Fine solid and/or liquid particles suspended in a gas phase.

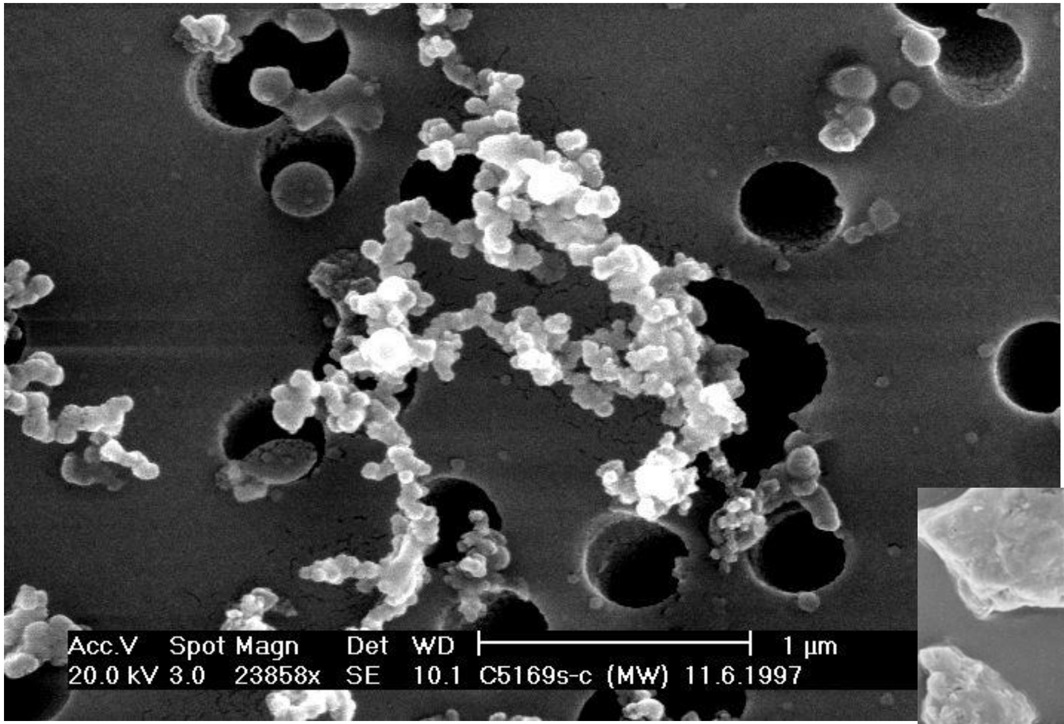
- **Size: a few nanometers (10^{-9} m) to tens of micrometers (10^{-6} m);**
- **Multi-phase system: solid-liquid-gas.**

Ammonium sulfate | **Sea salt**

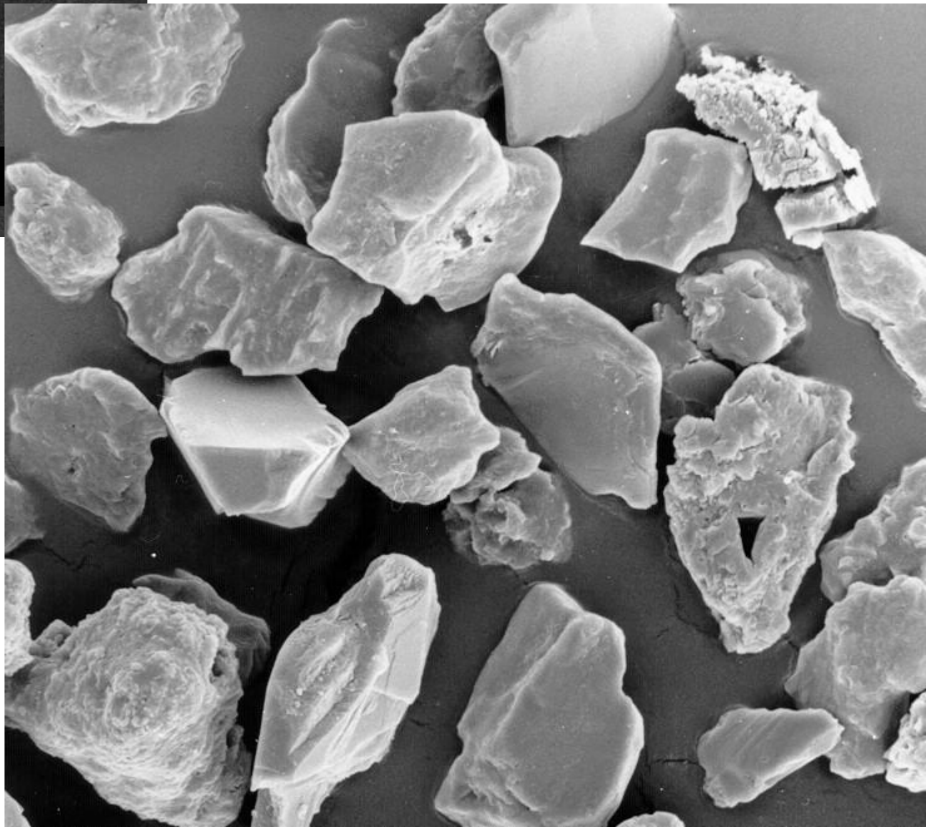




Black carbon



Dust



Primary vs. secondary aerosols

Primary

- Emitted directly as solid and/or liquid (sea salt, black carbon, dust, etc.)

Secondary

- Emitted as gas precursors, then converted into solid/liquid (the gas-to-particle conversion) (ammonium sulfate, secondary organic aerosol, etc.)

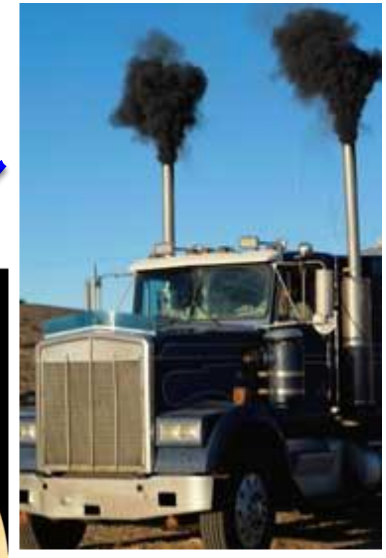
Gas-phase chemistry

$$SO_2 \xrightarrow{\cdot OH} SO_4^{2-}$$

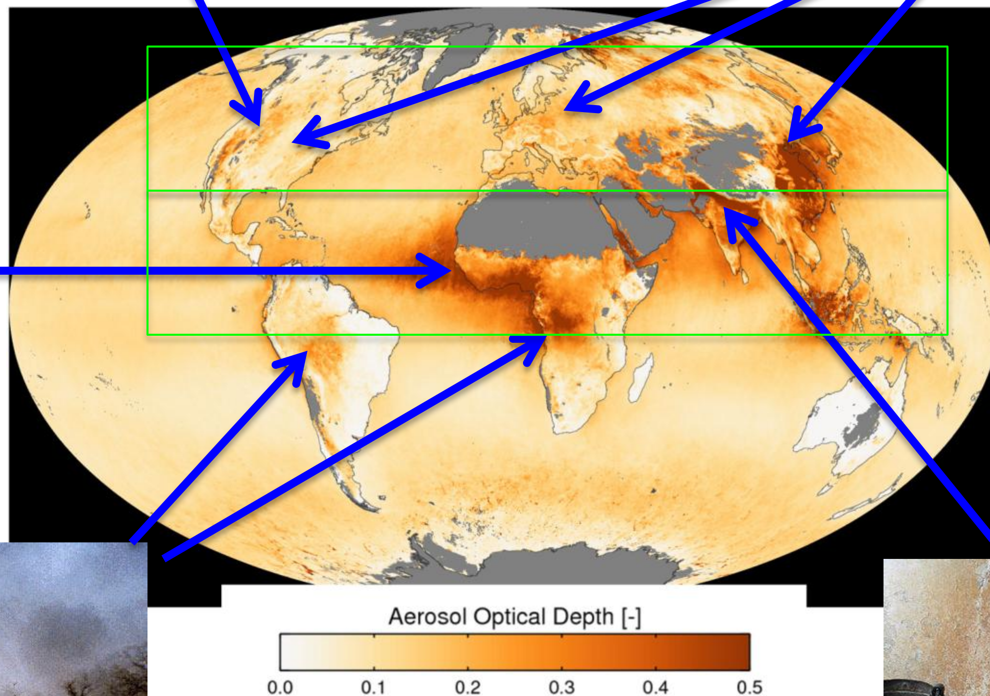
Natural and man-made aerosol sources

Wildfires

Fossil fuel burning

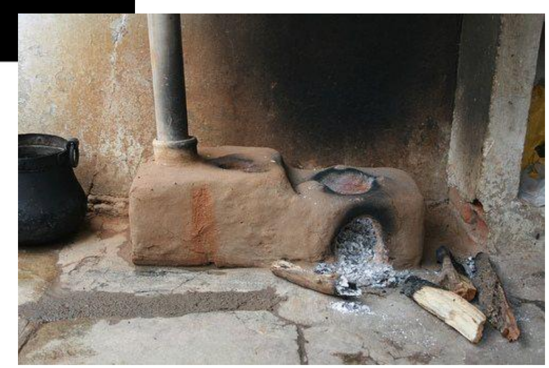


Desert dust



Biomass burning

Biofuel burning



A simple Beer's law calculation

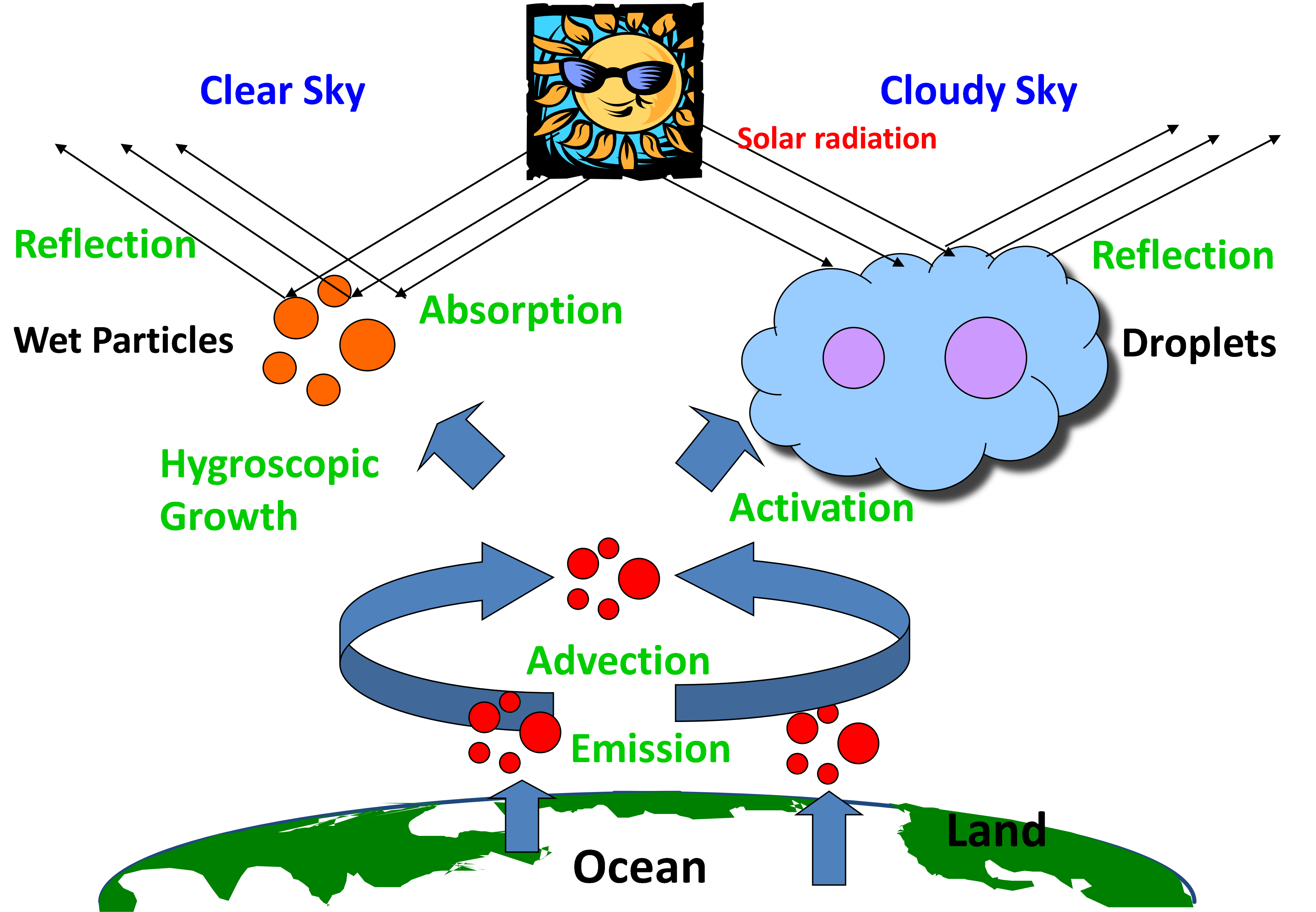
Aerosol extinction:

$$S_0(1 - \exp(-AOD)) \approx S_0 AOD$$

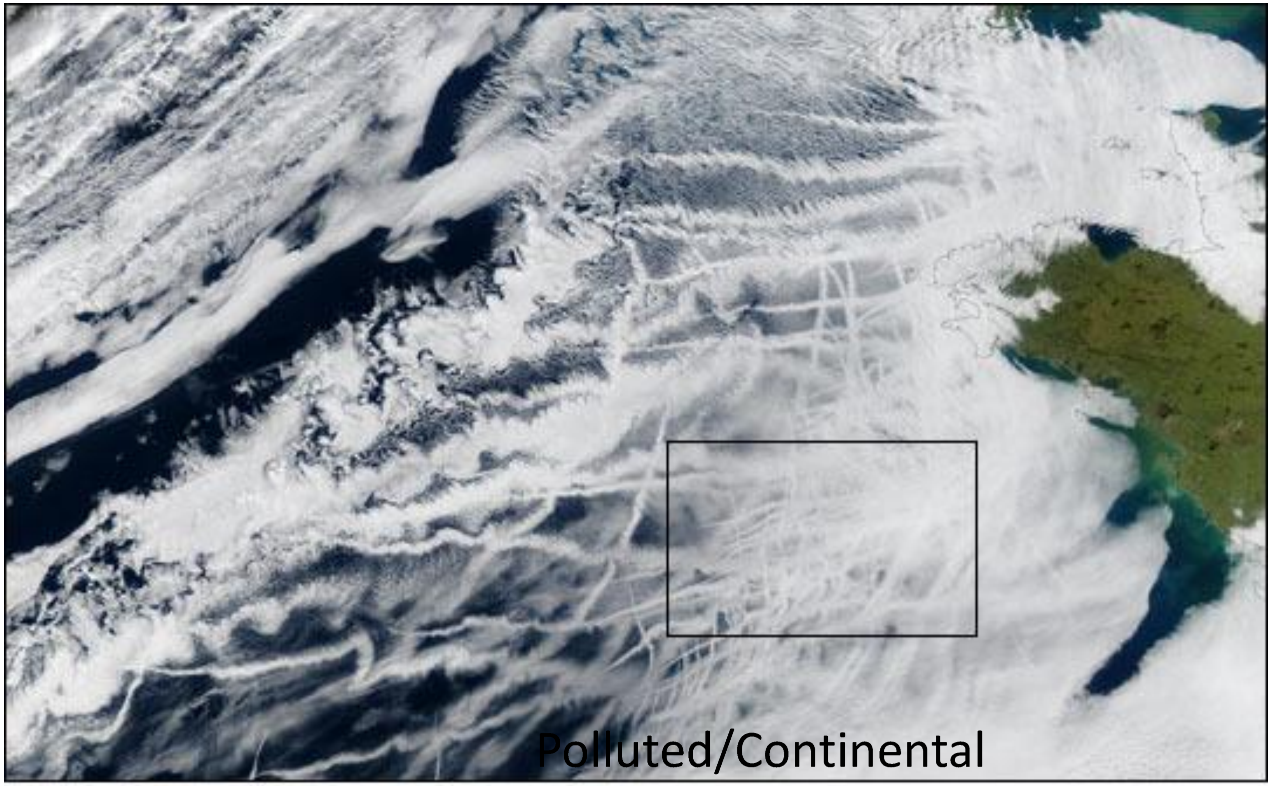
Solar radiation: ~ 300 W m^{-2}

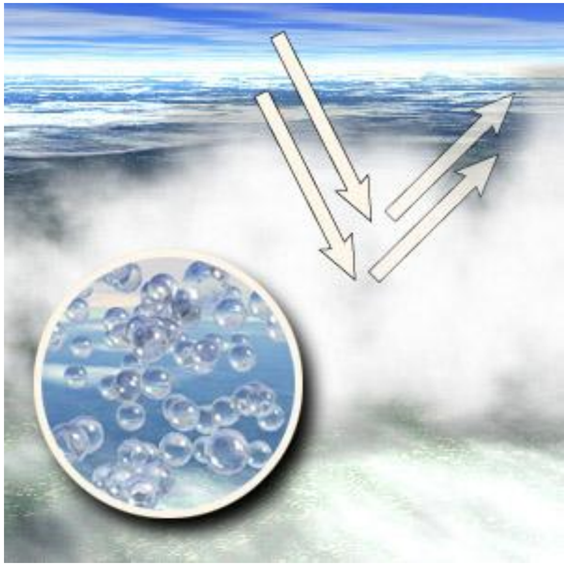
For an AOD of 0.1, the extinction is about 30 W m^{-2} locally.

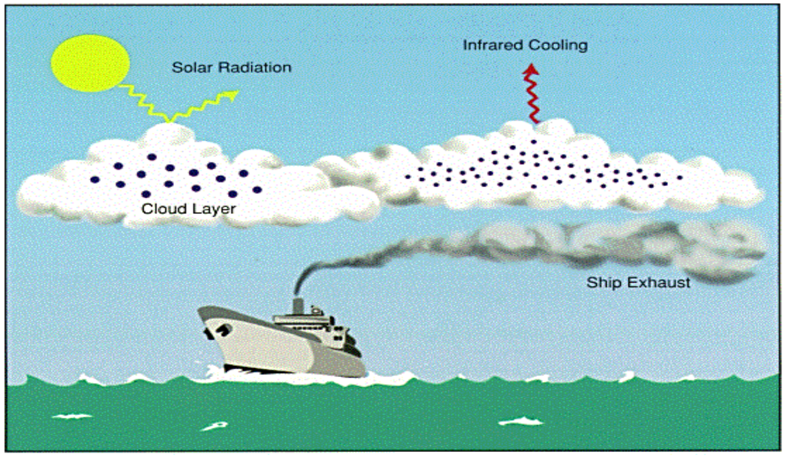
Aerosol-cloud-climate interactions



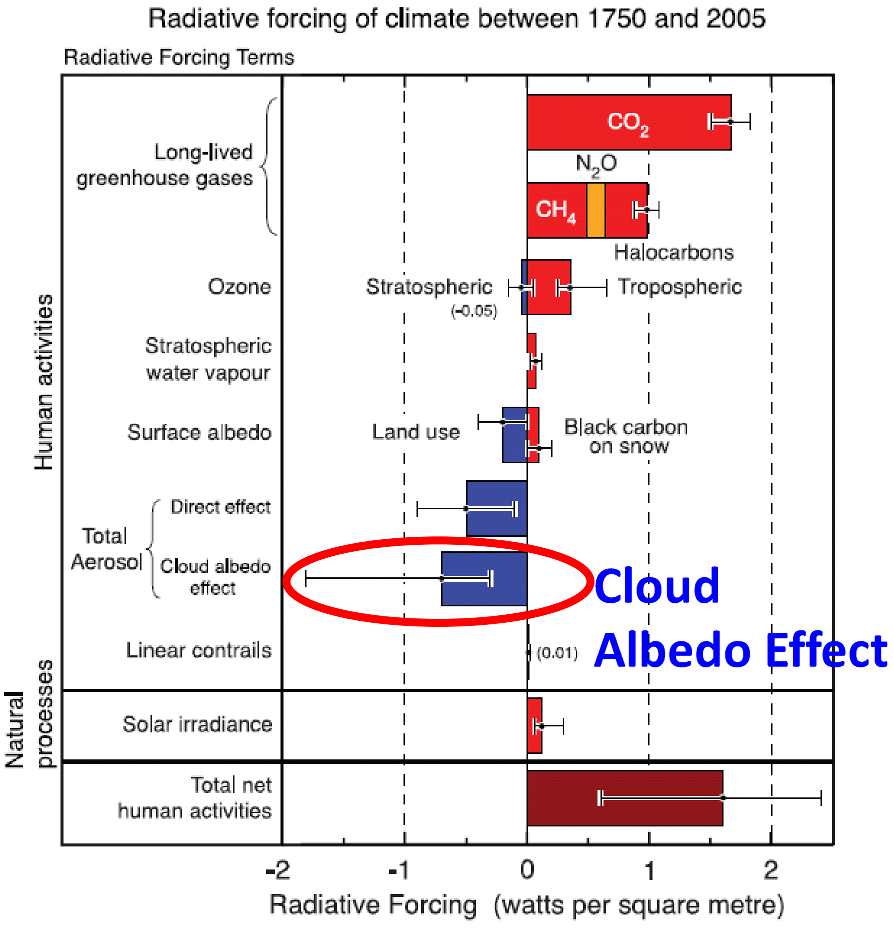
Ship track – indirect effects on display

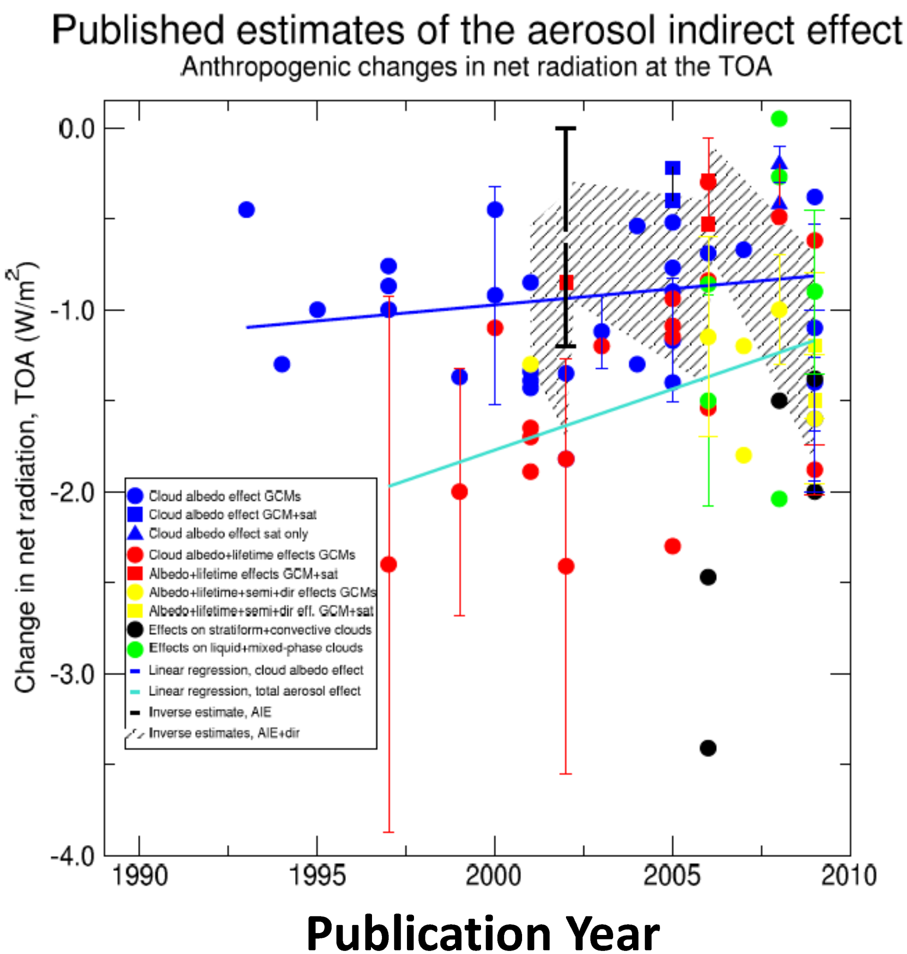






Aerosol-cloud interactions: the most uncertain radiative forcing



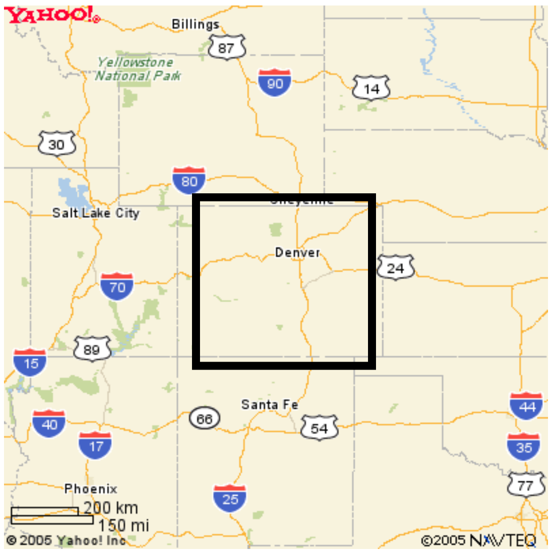


Foster et al. (2007)

Lohmann et al. (2010)

Modeling aerosol-cloud interactions on the global scale

How to reconcile the *spatial* and *temporal* gaps between General Circulation Models (GCM) and aerosol/cloud microphysics?



A typical GCM gridbox (~300 km ´ ~300 km)

<u>The size of Colorado</u>

Aerosols (~1 nm to ~1 μm)

<u>A continuous size distribution spanning 3 orders of magnitude</u>

Cloud droplets (10 μm to 30 μm)

A difference of 10 orders of magnitude!

A typical GCM timestep (30 min.)

A typical microphysics timestep (1 sec.)

A difference of 3 orders of magnitude!

Part 2: Aerosols in AM3/CM3

Representation of aerosols and clouds in AM3/CM3

- **Online aerosol transport**
- **Improved aerosol optics (internal mixing, hygroscopic growth, etc.)**
- **Aerosol-Liquid Cloud Interactions**

A prognostic scheme of cloud droplet number concentration (Ming et al., 2007) with an explicit treatment of aerosol activation at cloud base (Ming et al., 2006).

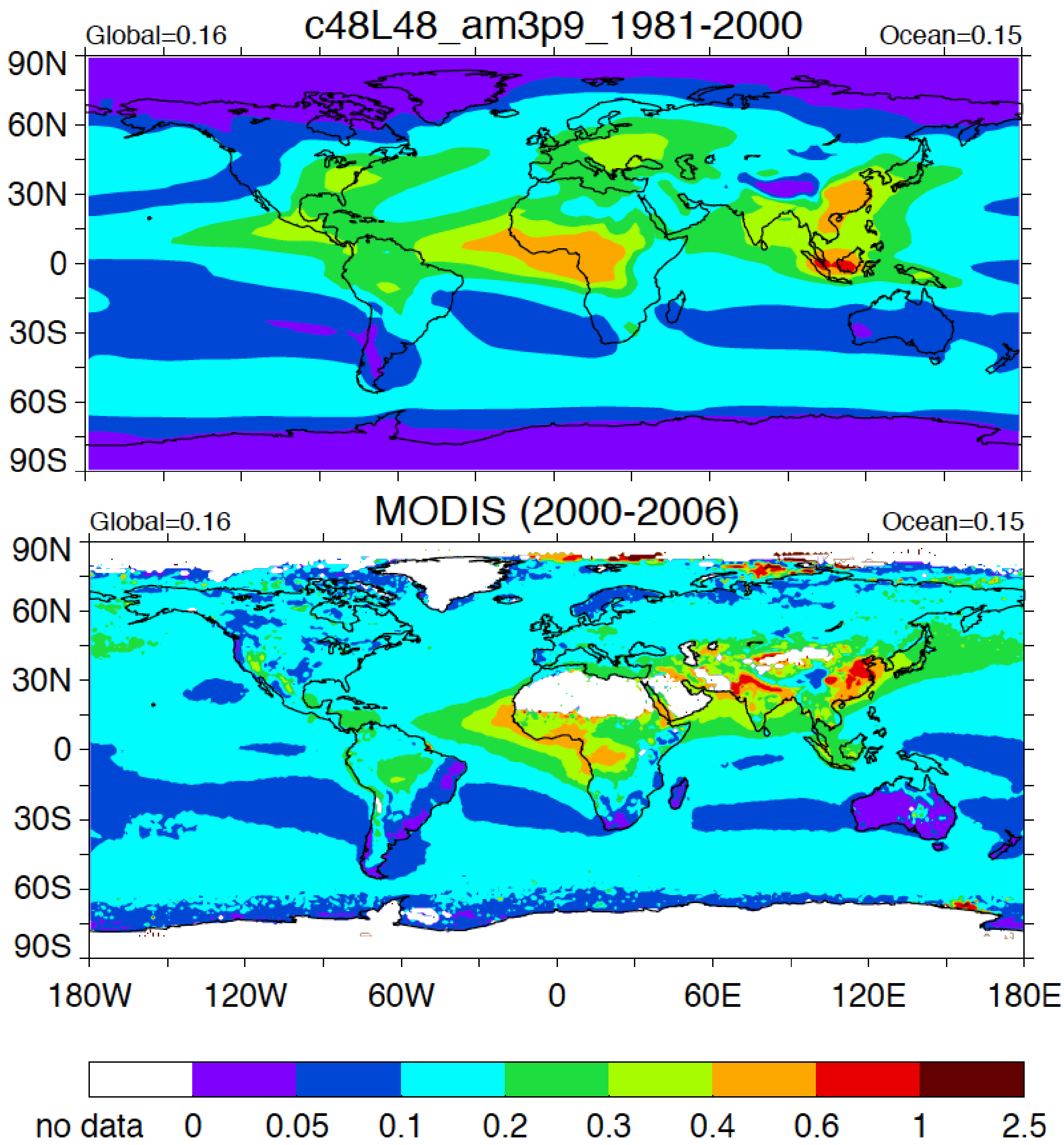
- **Convection Parameterization**

Move from the <u>relaxed Arakawa-Schubert (RAS)</u> in CM2 to the <u>Donner deep convection scheme</u> (Donner, 1993) and the <u>University of Washington (UW) shallow convection scheme</u> (Bretherton et al., 2003). By providing in-plume updraft velocity, the latter two are ideal for implementing aerosol/cloud microphysics.

Anthropogenic aerosol radiative flux perturbation (RFP, W m^{-2}) at TOA from pre-industrial to present-day

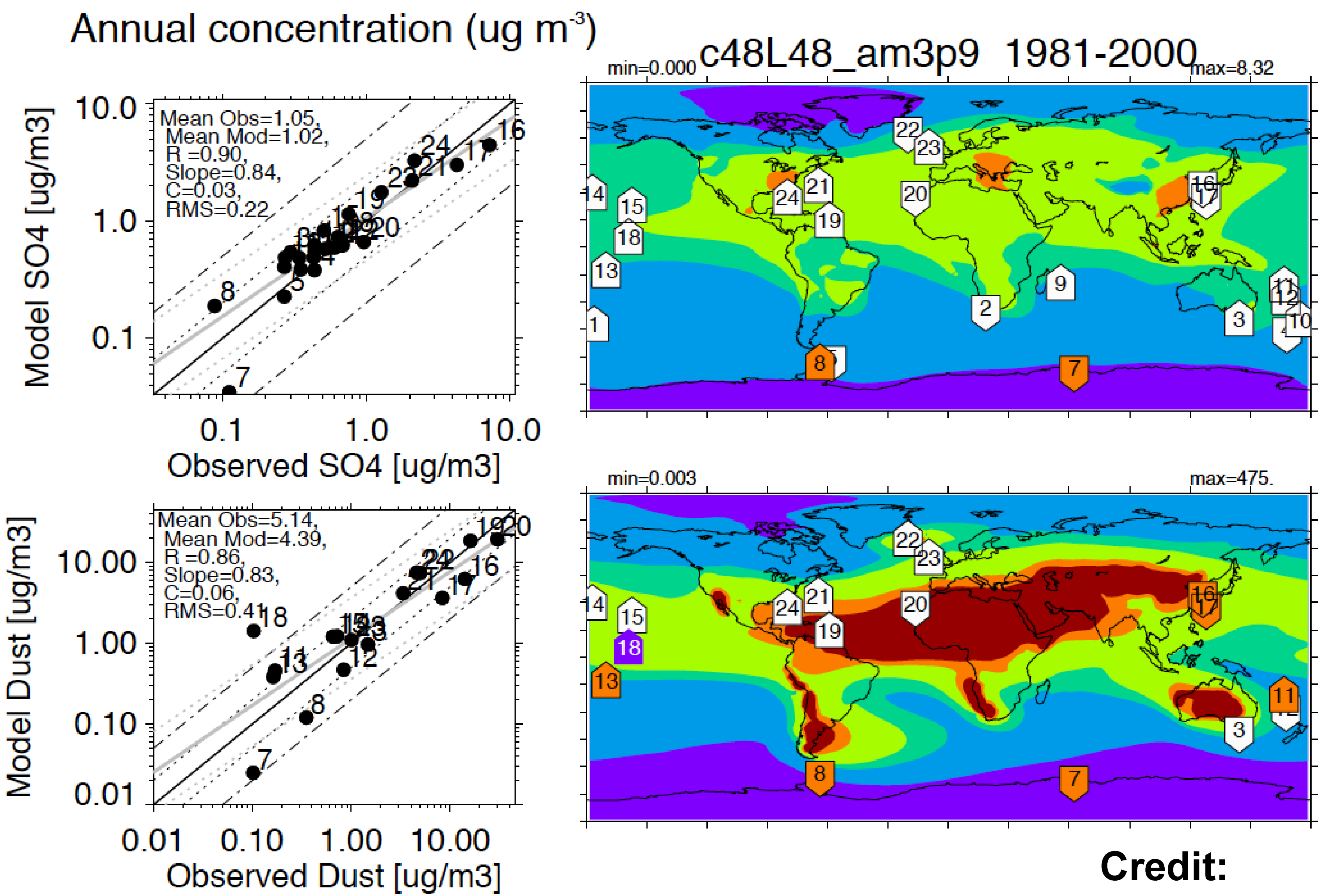
	AM3 (to be used for AR5)	AM2 (used for AR4)
Direct effects – Sulfate and organic carbon	0 (assuming internal mixing of sulfate and black carbon)	-1.3 (external mixing)
Direct effects - Black carbon		0.5 (external mixing)
Indirect effects	-1.3	Not included

Aerosol optical depth



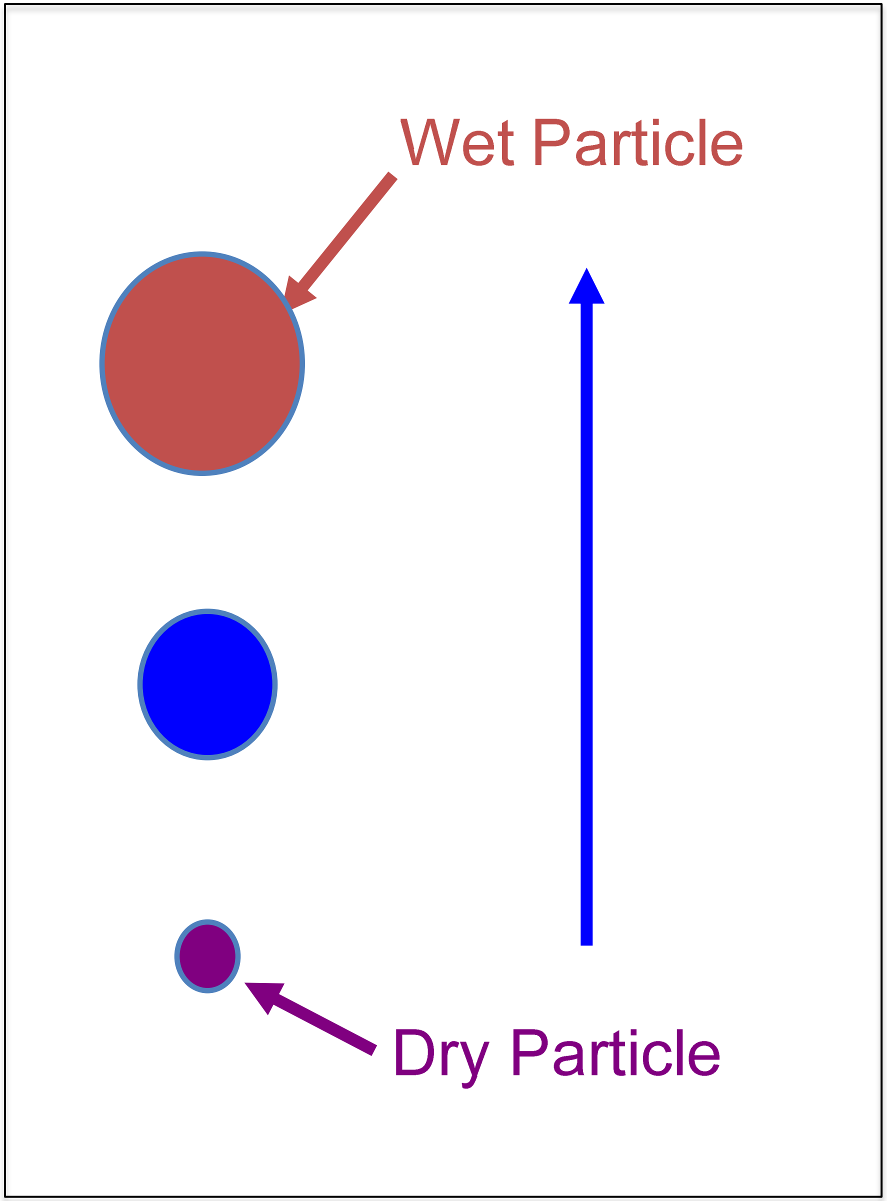
Credit: Paul Ginoux

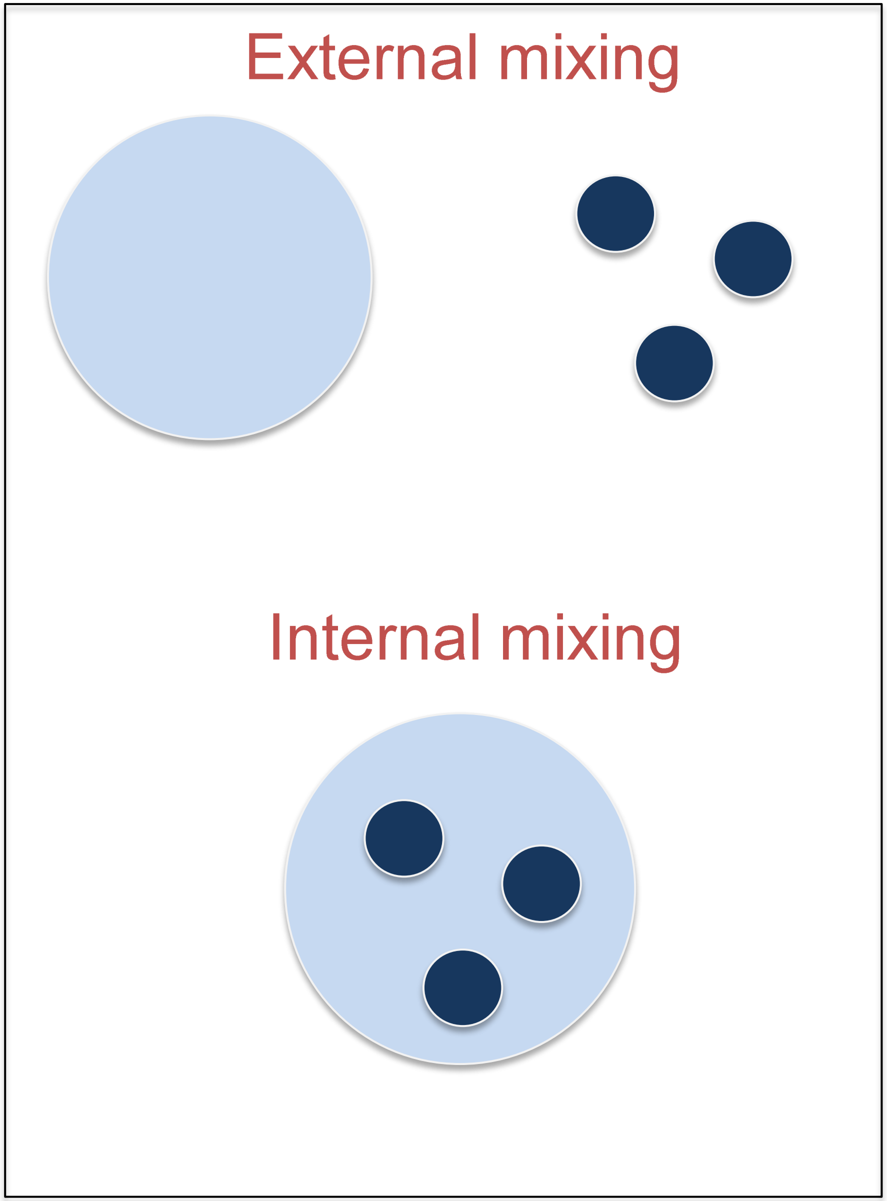
Aerosol surface concentrations



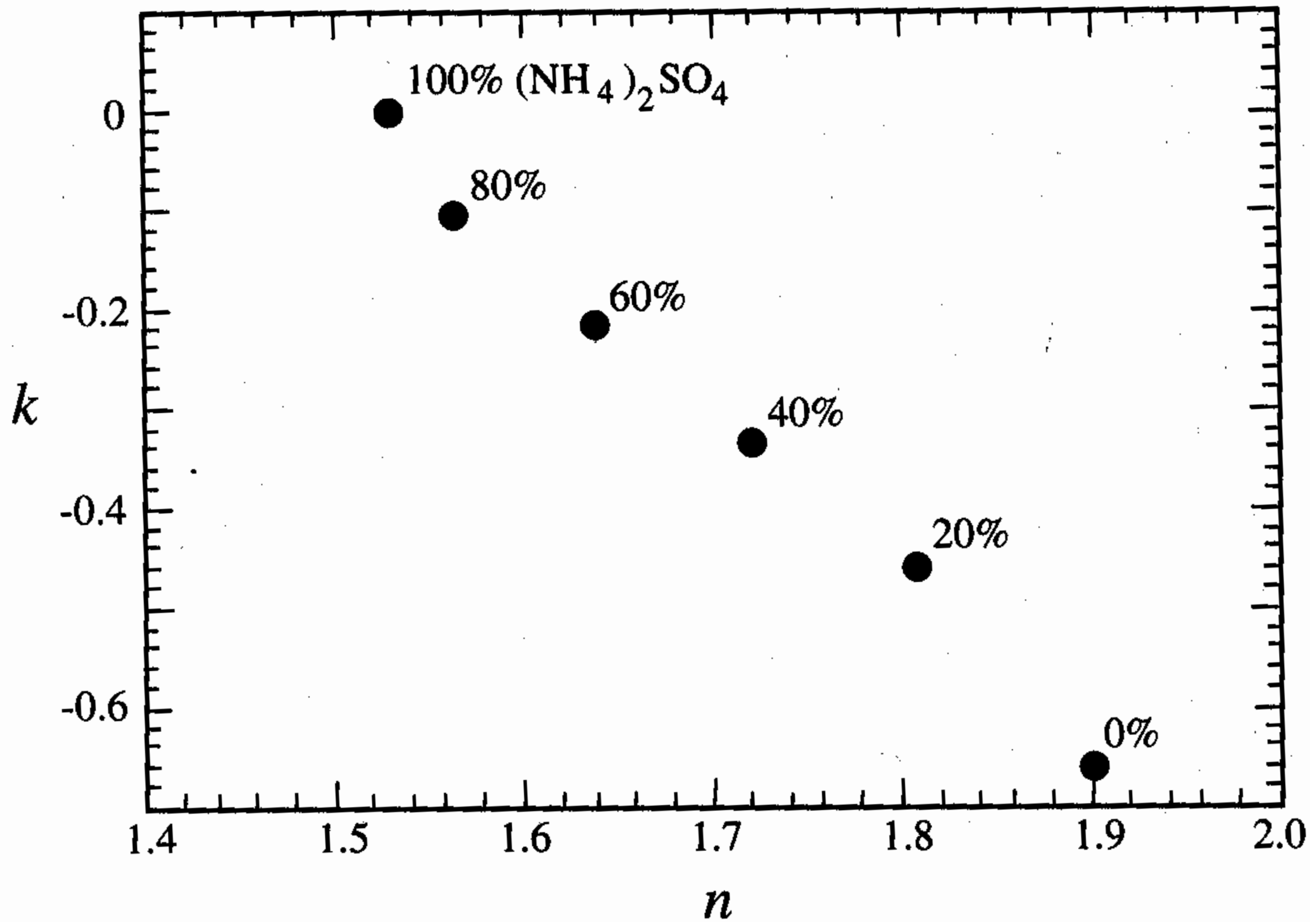
Credit: Paul Ginoux

Hygroscopic growth & internal mixing





Effects of internal mixing: refractive indices



URE 22.26 Real (n) and imaginary (k) parts of the refractive indices of internally mixed soot $(NH_4)_2SO_4$ particles.

Effects of internal mixing: scattering/absorbing coefficients

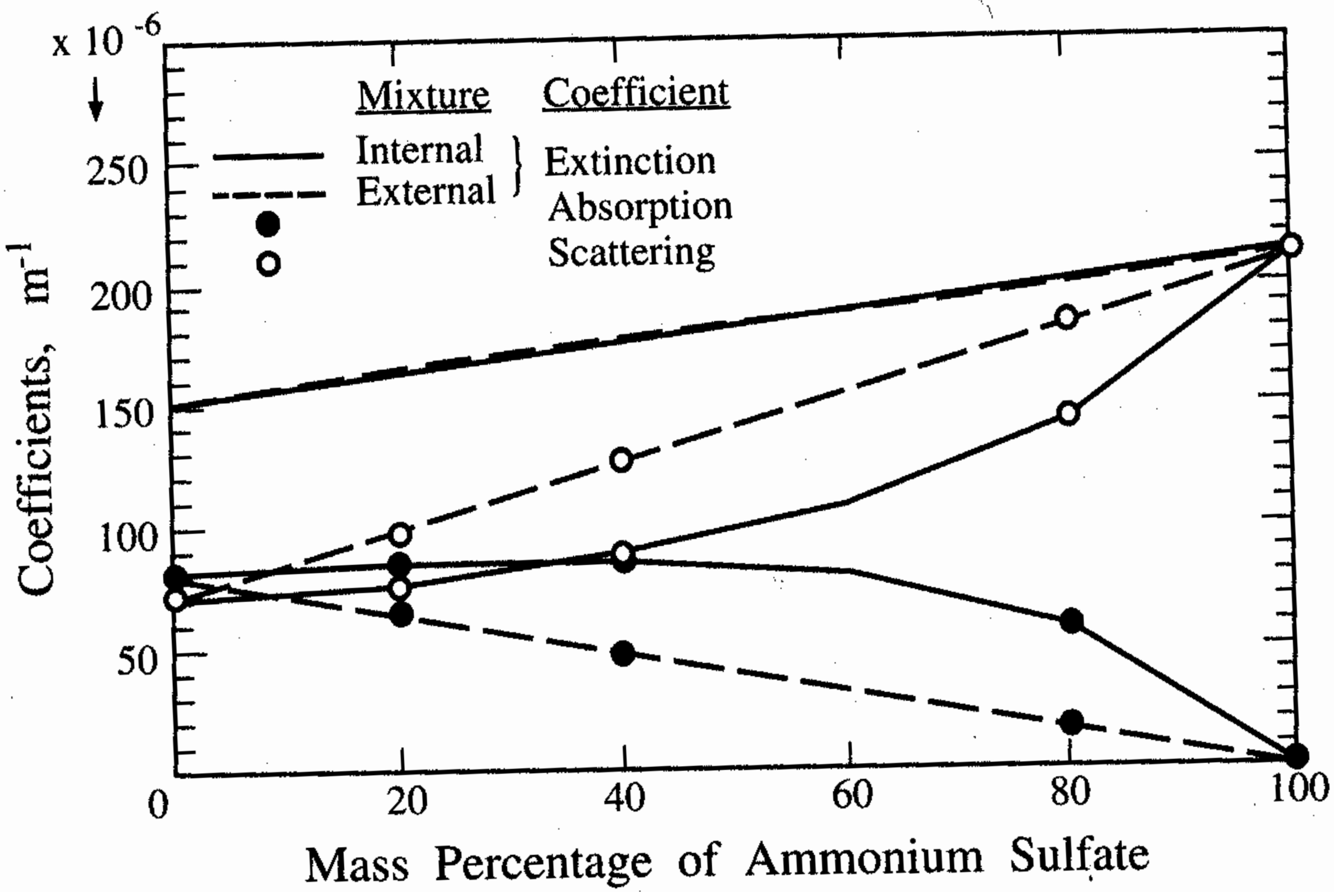


FIGURE 22.24 Total extinction, scattering, and absorption coefficients for internal versus external mixtures of soot and $(NH_4)_2SO_4$.

Effects of internal mixing: single-scattering albedo

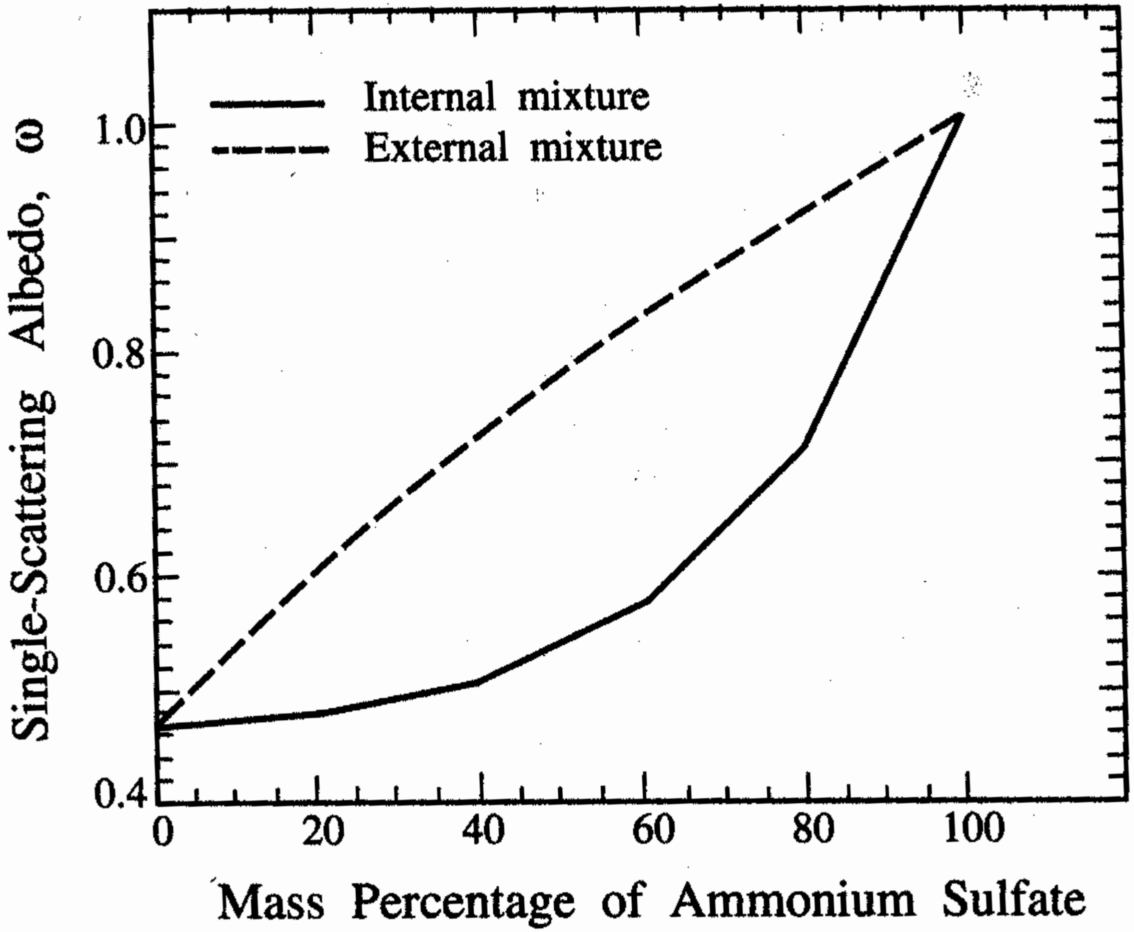
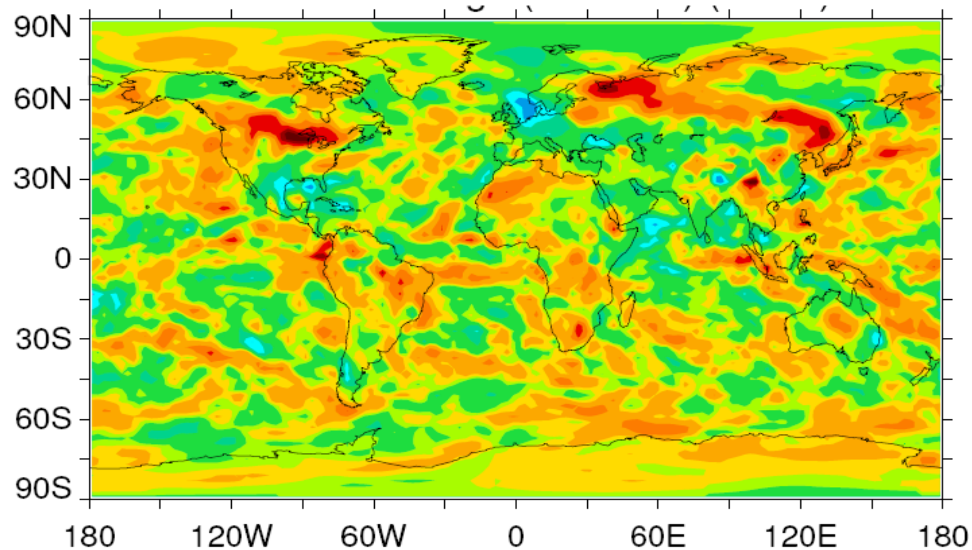


FIGURE 22.25 Single-scattering albedo for internal versus external mixture of soot and $(NH_4)_2SO_4$.

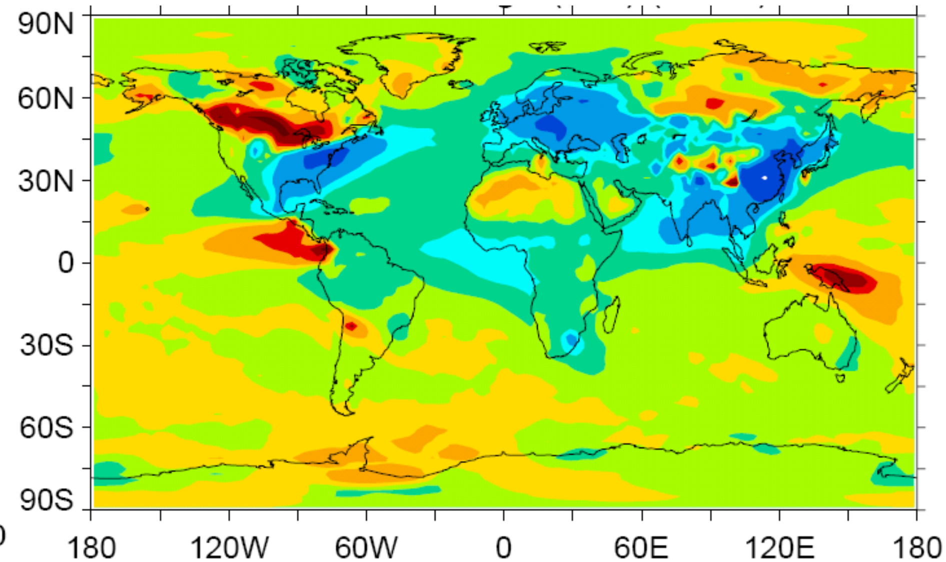
Aerosol direct effects

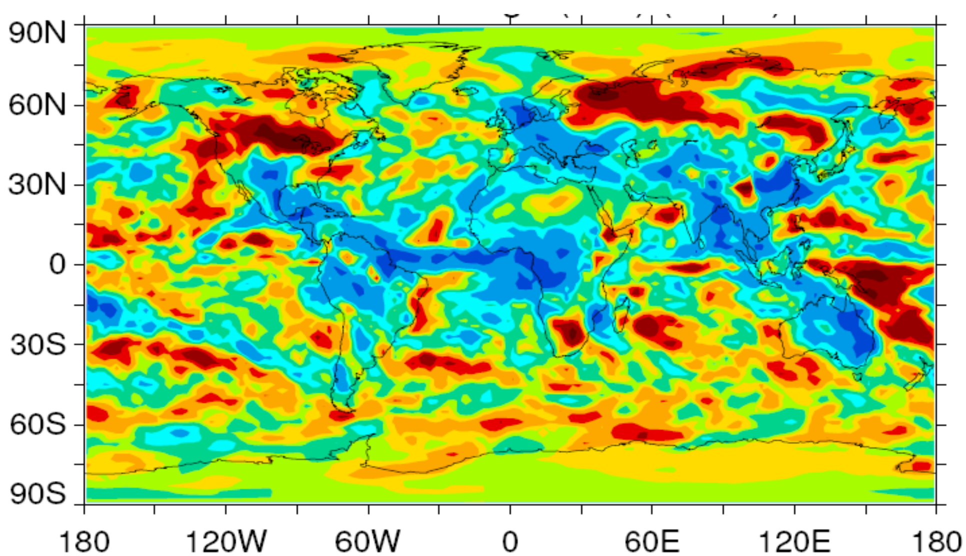
Importance of atmospheric absorption

TOA – all-sky ***0 W m^{-2}***



TOA – clear-sky ***-1.0 W m^{-2}***





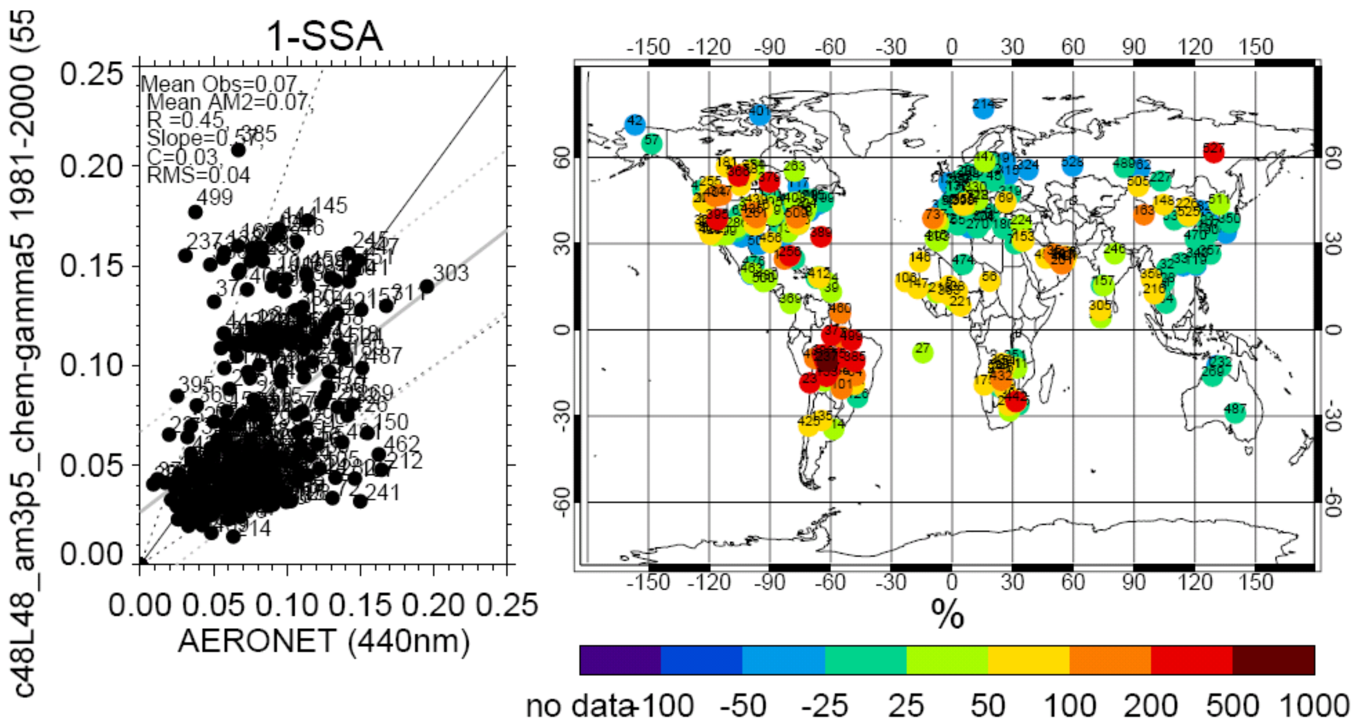
Surface – all-sky

-1.3 W m^{-2}

A sanity check on aerosol absorption

Comparison with AERONET measurements of co-albedo

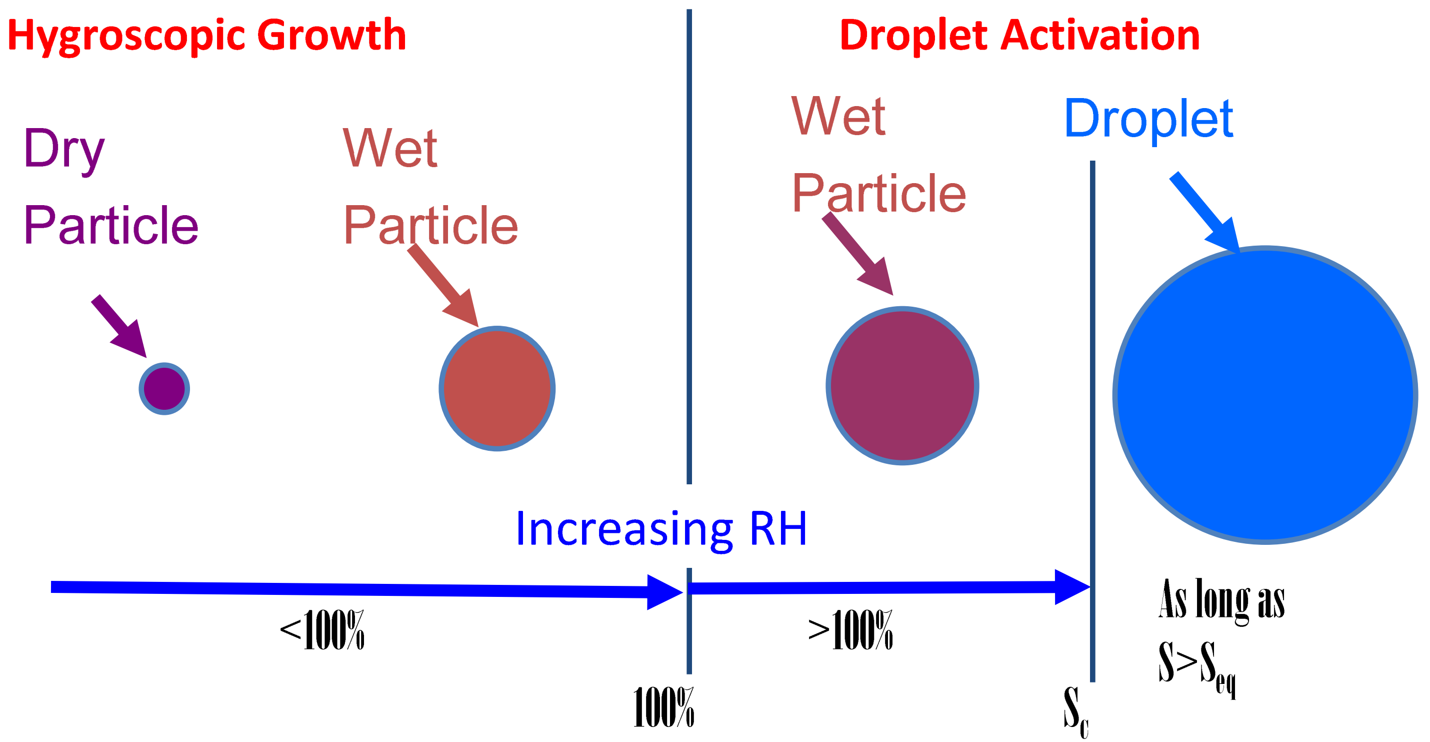
AM3



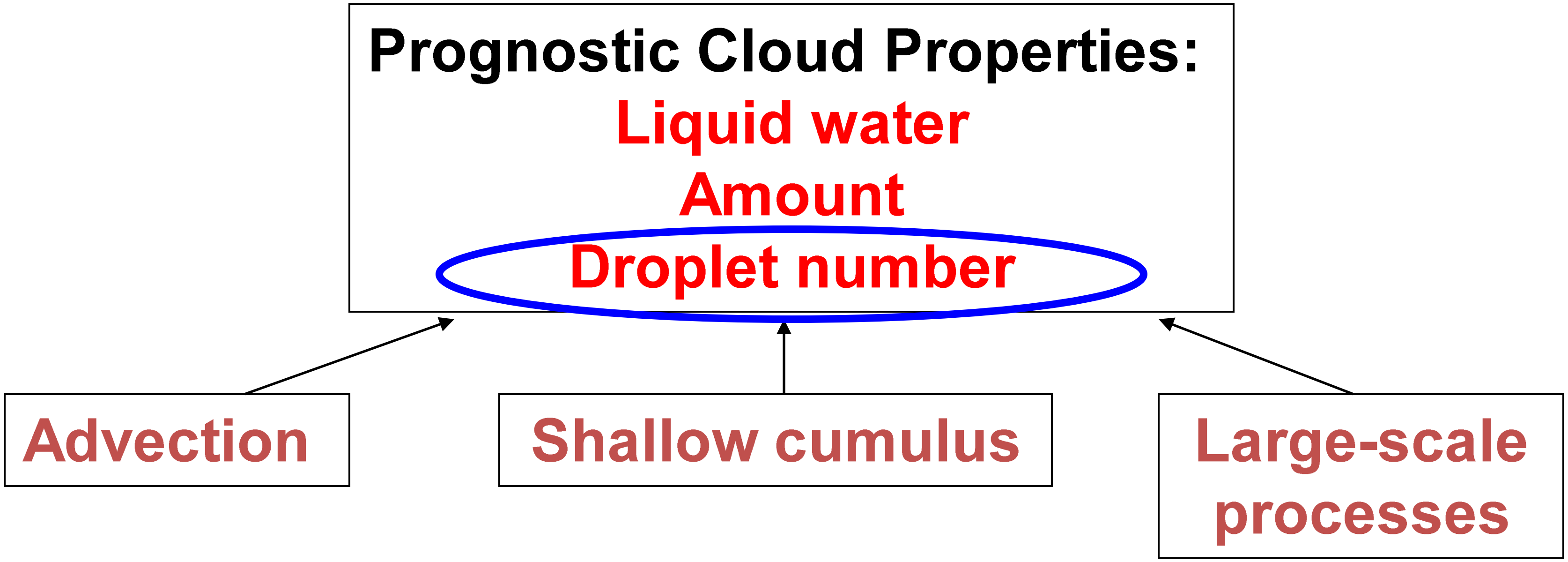
Credit:
Paul Ginoux

To initialize nucleation of droplets in saturated water vapor:

- **In the absence of CCN, s must be *several hundreds percents* (unrealistically high in the atmosphere);**
- **In the presence of CCN, s typically needs to be *less than one percent*.**



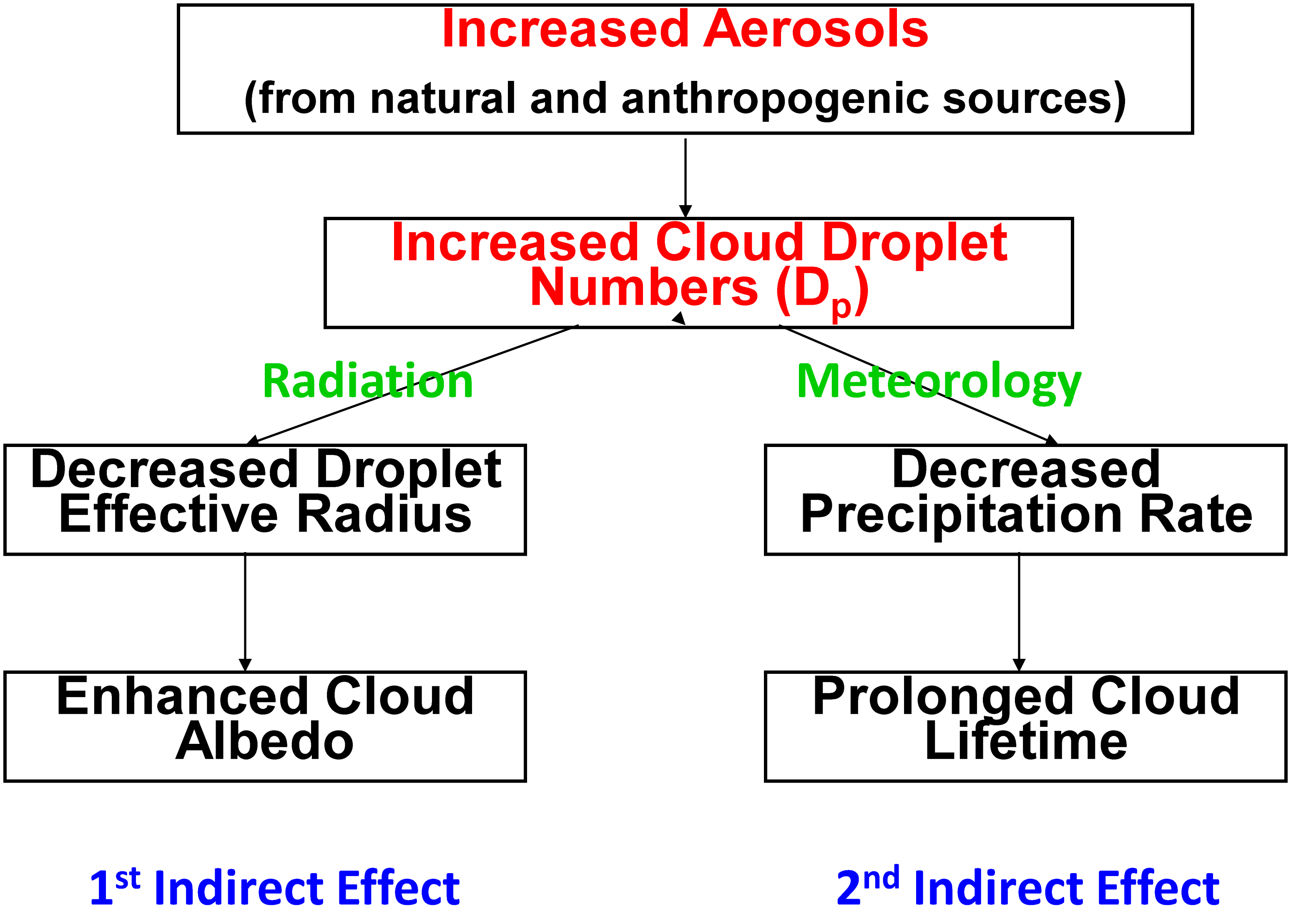
A prognostic treatment of aerosol-liquid cloud interactions



- Source and sink terms are fully consistent;
- Multiple aerosol species (i.e., sulfate, organic carbon and sea salt) are activated;
- Droplets evolve freely with model meteorology.

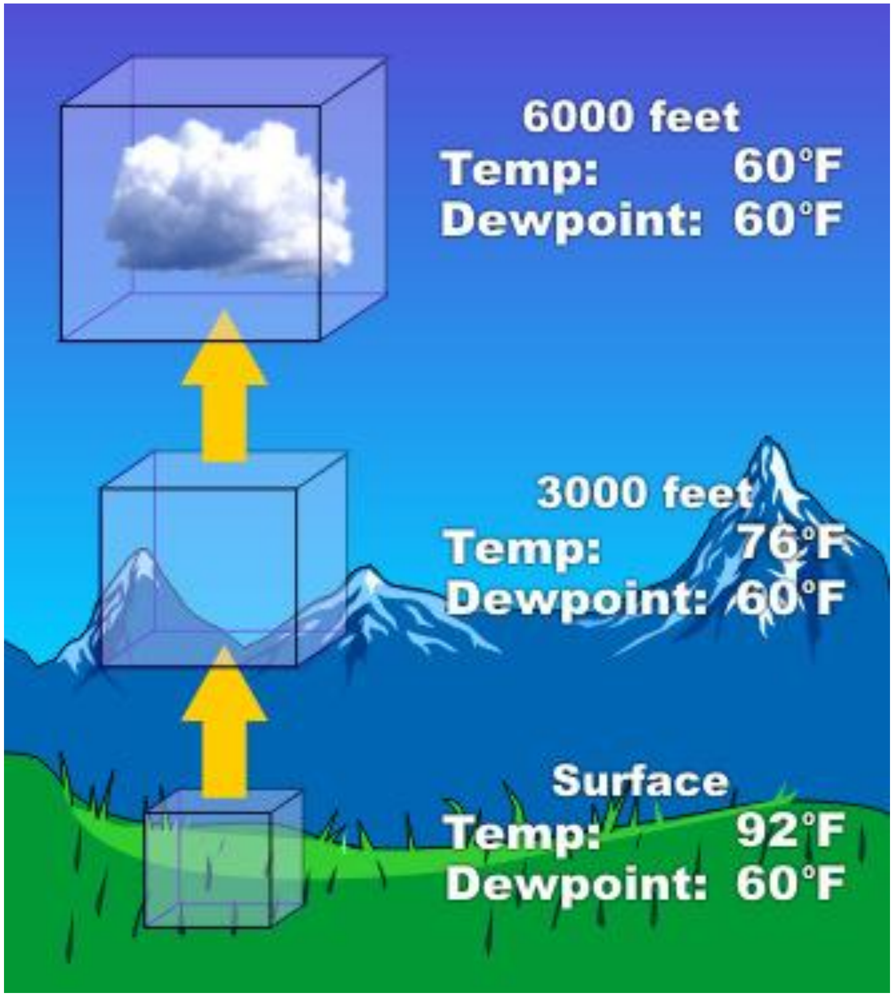
Ming et al. (2007)

1st and 2nd indirect radiative effects of aerosols

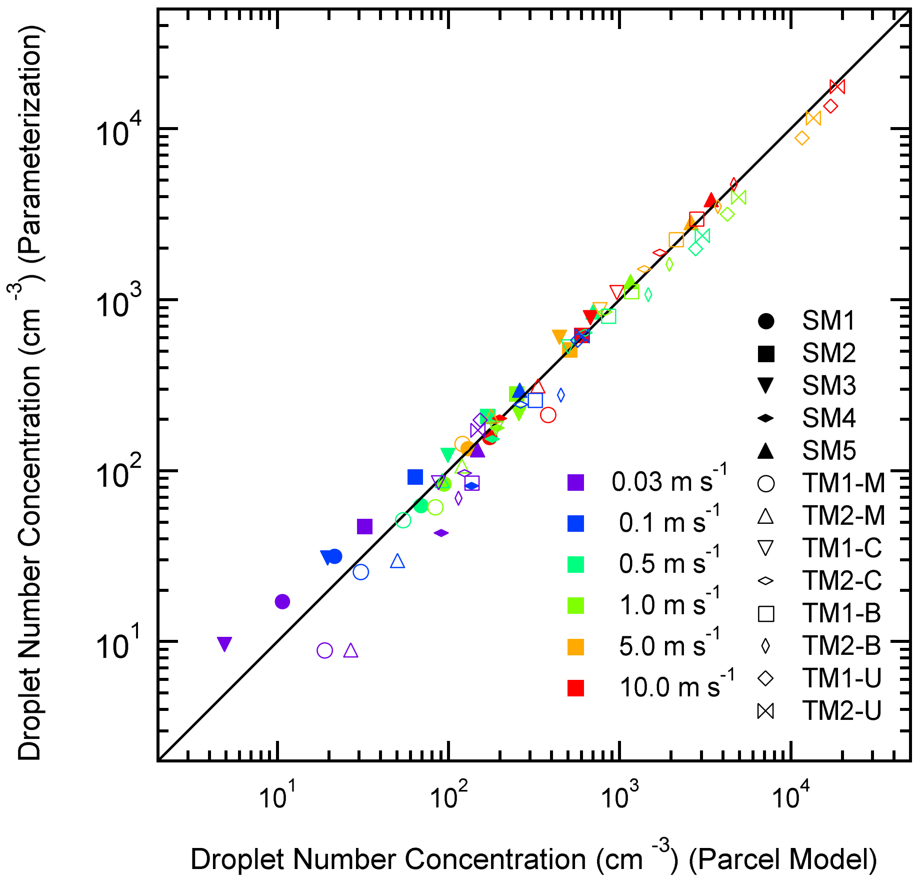


Parameterization of Droplet Activation

Cloud parcel model



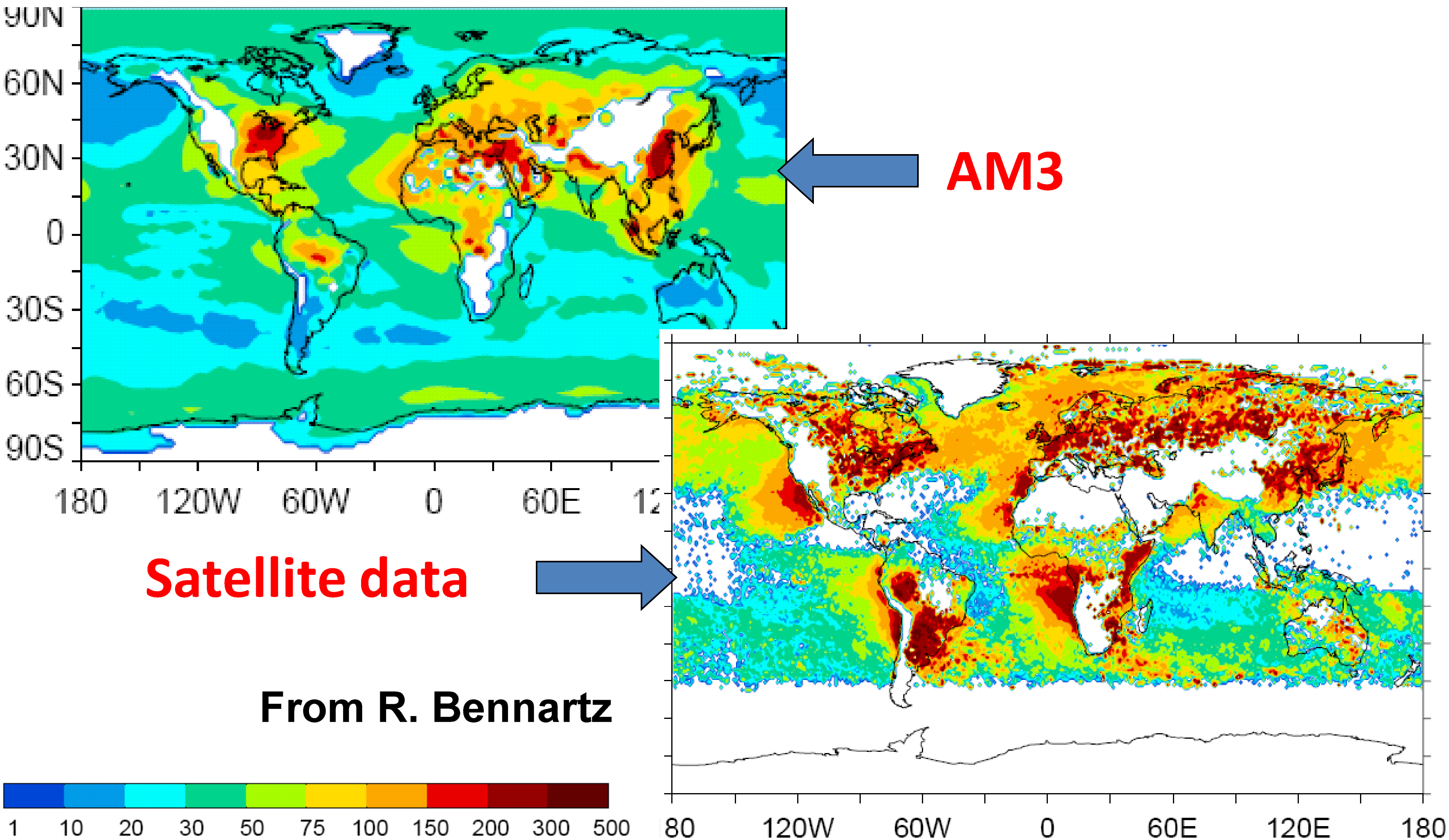
Parameterization



Ming et al. (2006)

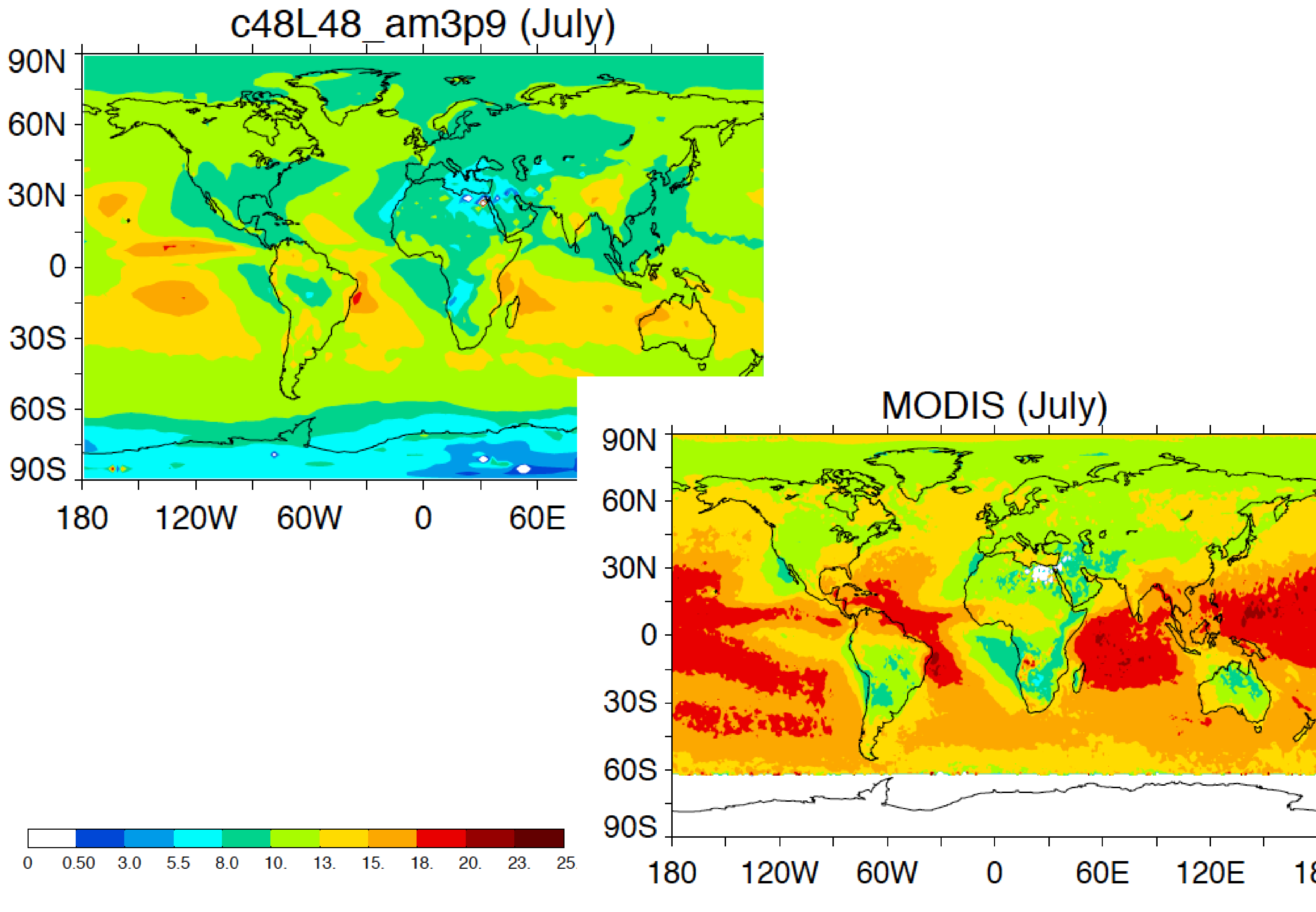
Comparison of AM3-simulated cloud properites with satellite data

925-hPa Cloud droplet number concentration (cm^{-3}) in July

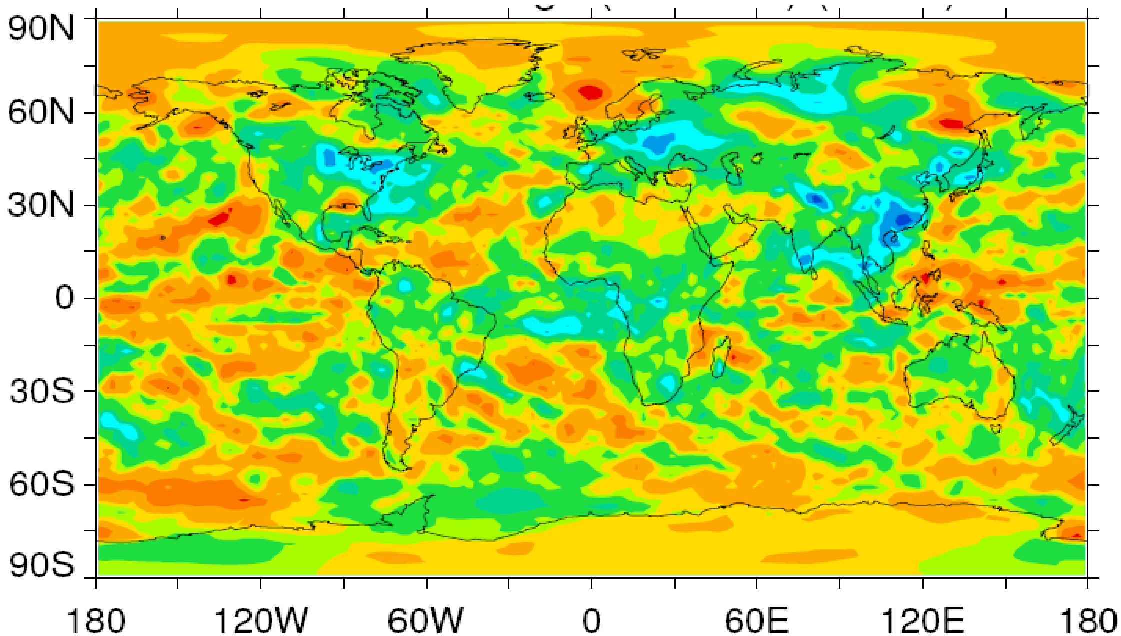


From R. Bennartz

Cloud effective radius (μm)

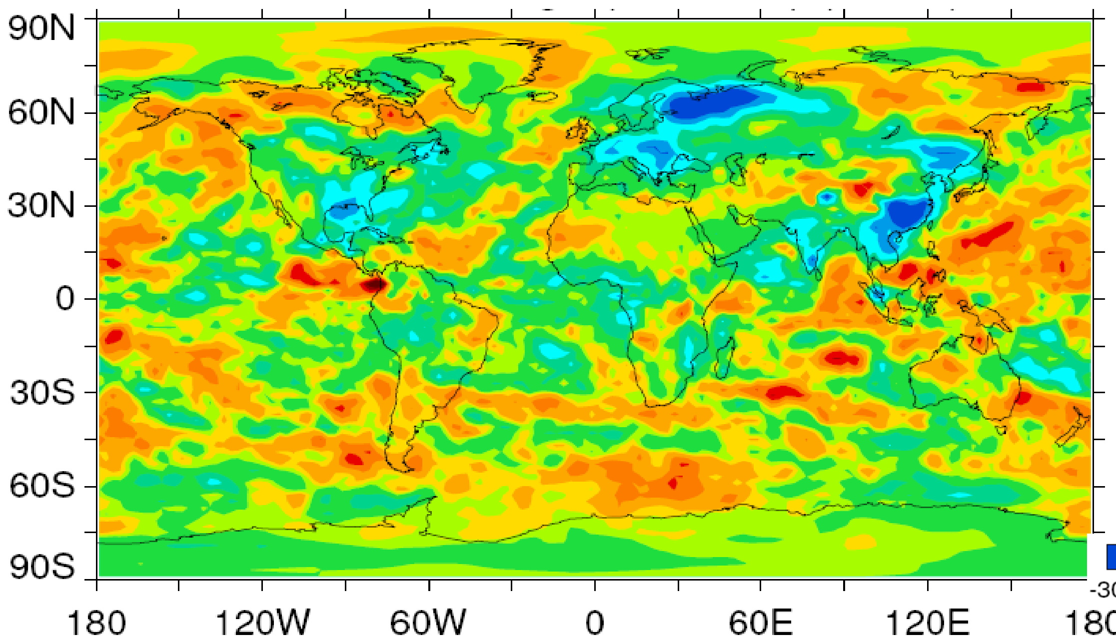


1st and 2nd aerosol indirect effects



1st Indirect Effect

-0.6 W m^{-2}



2nd Indirect Effect

-0.6 W m^{-2}

Part 3: CM3-facilitated science

A "top-down" approach toward understanding regional climate change

Global-mean

↓

Zonal-mean

↓

Zonal asymmetry

Why not "bottom-up"?

•Both local forcing and large-scale circulation change are important;

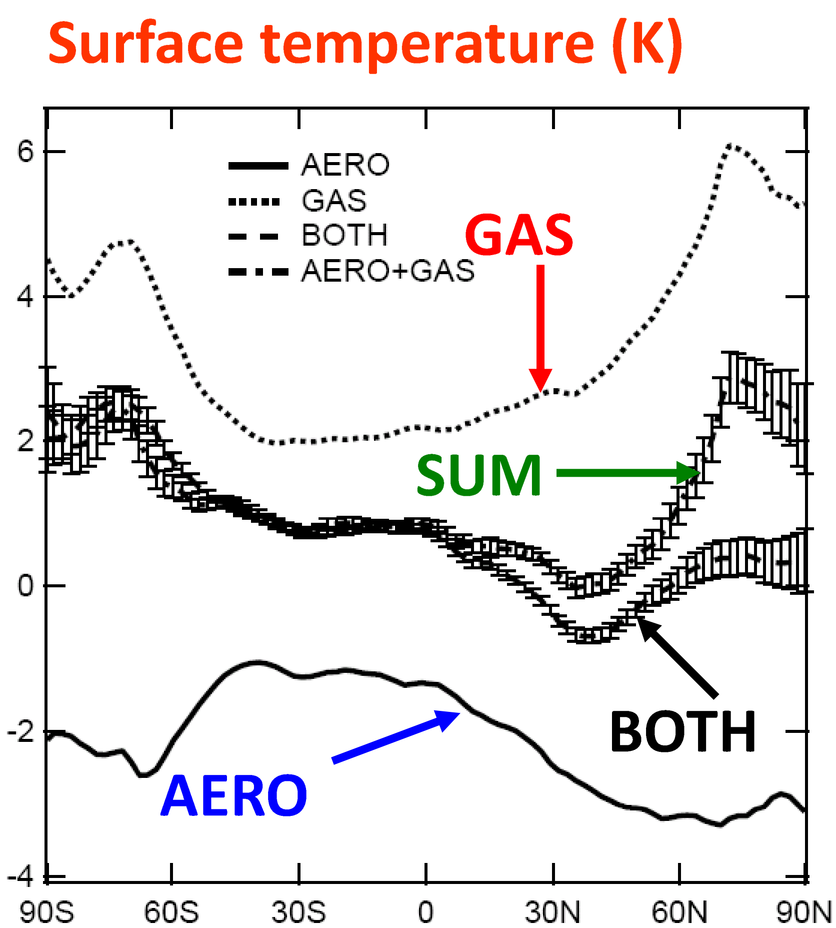
•The finer the spatial scale is, the less constrained the regional climate system is.

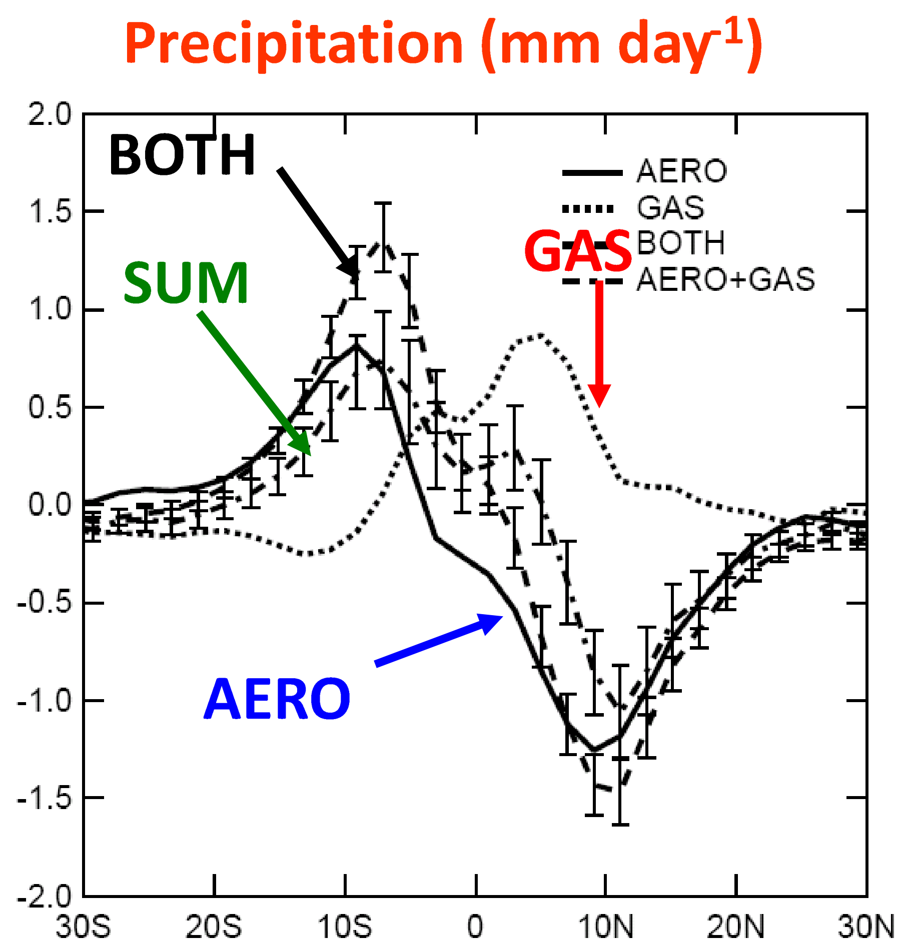
EVEN MORE recommendations for your summer reading list

- Ming, Y., V. Ramaswamy, and G. Persad, 2010: Two opposing effects of absorbing aerosols on global-mean precipitation. ***Geophysical Research Letter***, doi:10.1029/2010GL042895.
- G. Persad, Ming, Y., and V. Ramaswamy, 2011: Tropical tropospheric-only responses to absorbing aerosols. ***Journal of Climate***, doi:10.1175/JCLI-D-11-00122.1.
- Ming, Y., and V. Ramaswamy, 2011: A Model Investigation of Aerosol-induced Changes in Tropical Circulation. ***Journal of Climate***, doi:10.1175/2011JCLI4108.1.
- Ming, Y., V. Ramaswamy, and G. Chen, 2011: A Model Investigation of Aerosol-induced Changes in Boreal Winter Extratropical Circulation. ***Journal of Climate***, doi:10.1175/2011JCLI4111.1.
- Bollasina, M.A., Y. Ming, and V. Ramaswamy, 2011: Anthropogenic Aerosols and the Weakening of the South Asian Monsoon. ***Science***, doi:10.1126/science.1204994.

Zonal-mean responses to aerosols and greenhouse gases

- **Dipole pattern of tropical rainfall change;**
- **Role of the thermodynamic control (C-C).**





Ming and Ramaswamy (2009)

Science AAAS

REPORTS

Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon

Massimo A. Bollasina,[1] Yi Ming,[2]* V. Ramaswamy[2]

Observations show that South Asia underwent a widespread summertime drying during the second half of the 20th century, but it is unclear whether this trend was due to natural variations or human activities. We used a series of climate model experiments to investigate the South Asian monsoon response to natural and anthropogenic forcings. We find that the observed precipitation decrease can be attributed mainly to human-influenced aerosol emissions. The drying is a robust outcome of a slowdown of the tropical meridional overturning circulation, which compensates for the aerosol-induced energy imbalance between the Northern and Southern Hemispheres. These results provide compelling evidence of the prominent role of aerosols in shaping regional climate change over South Asia.

Importance of the South Asian monsoon

A socio-economic view

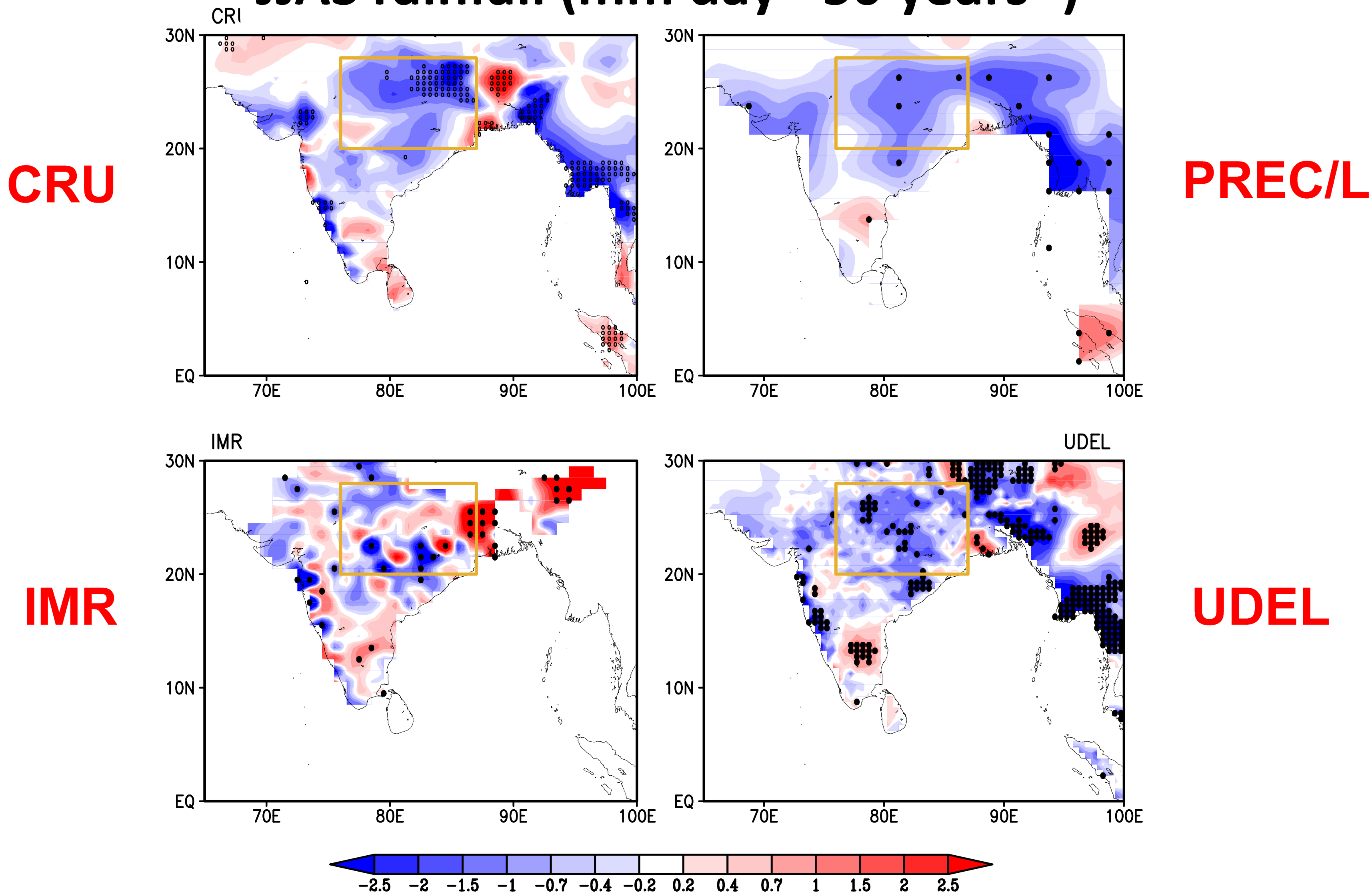
- South Asia is home to 20% of the world's population;
- The summer monsoon provides 80% of the annual-mean precipitation.

A physical climate view

- A manifestation of the summer tropical meridional (Hadley) circulation;
- Impacts on other regions (e.g., the Mediterranean).

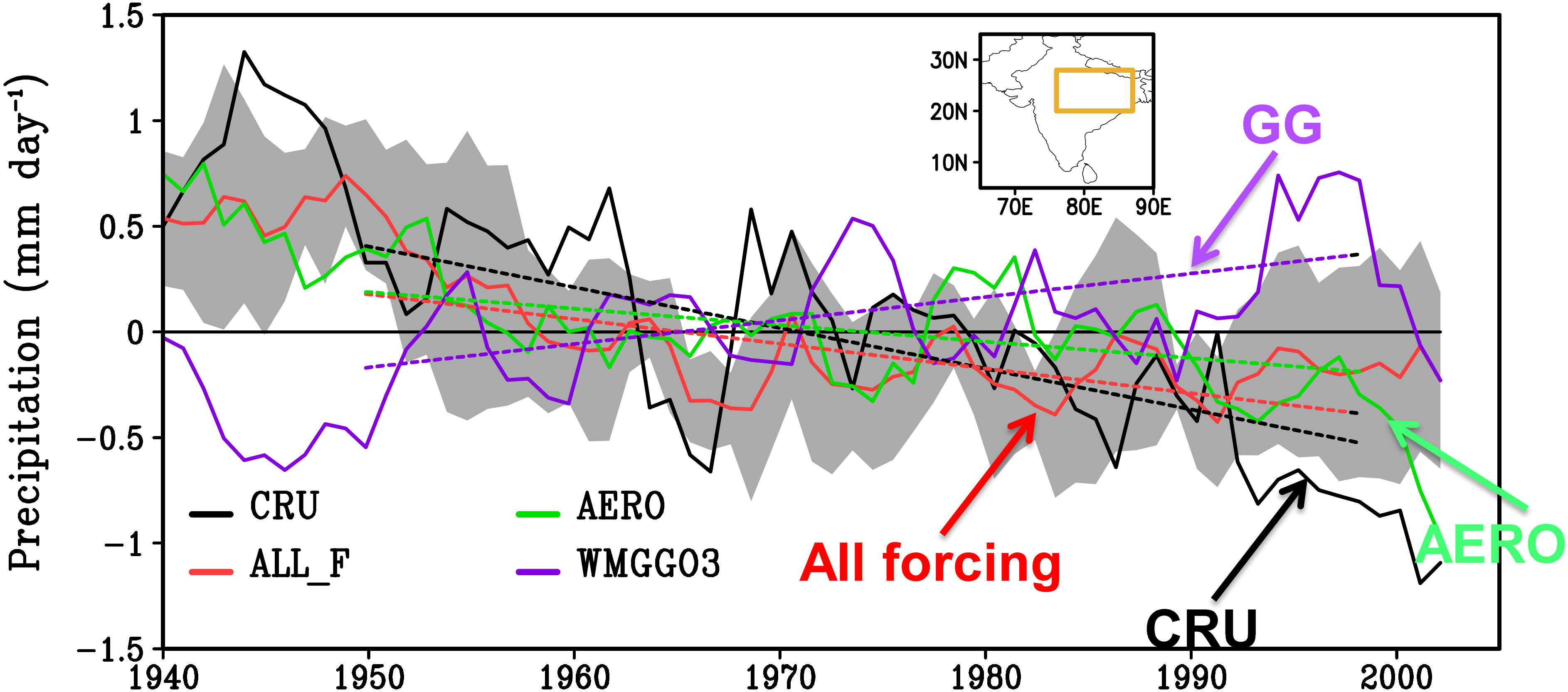
A drying trend over central-northern India during the second half of the 20th century

JJAS rainfall (mm day^{-1} 50 years^{-1})

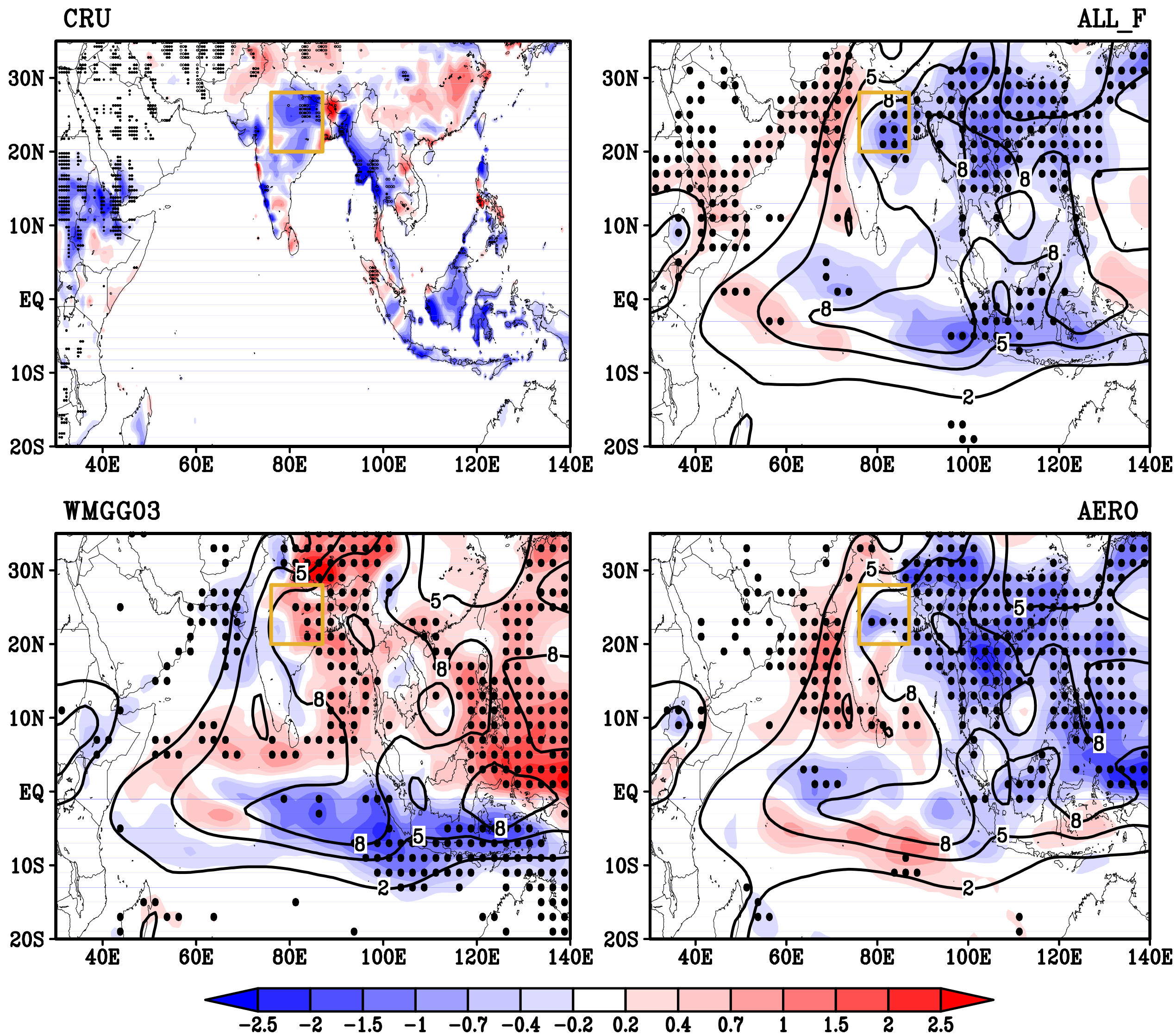


Attribution of the recent trend of the South Asian summer monsoon using CM3 historical simulations

Linear trends of average JJAS rainfall over central-northern Indian (mm day^{-1})



Spatial pattern of linear trends of JJAS rainfall ($mm\ day^{-1}\ 50\ years^{-1}$)



CRU

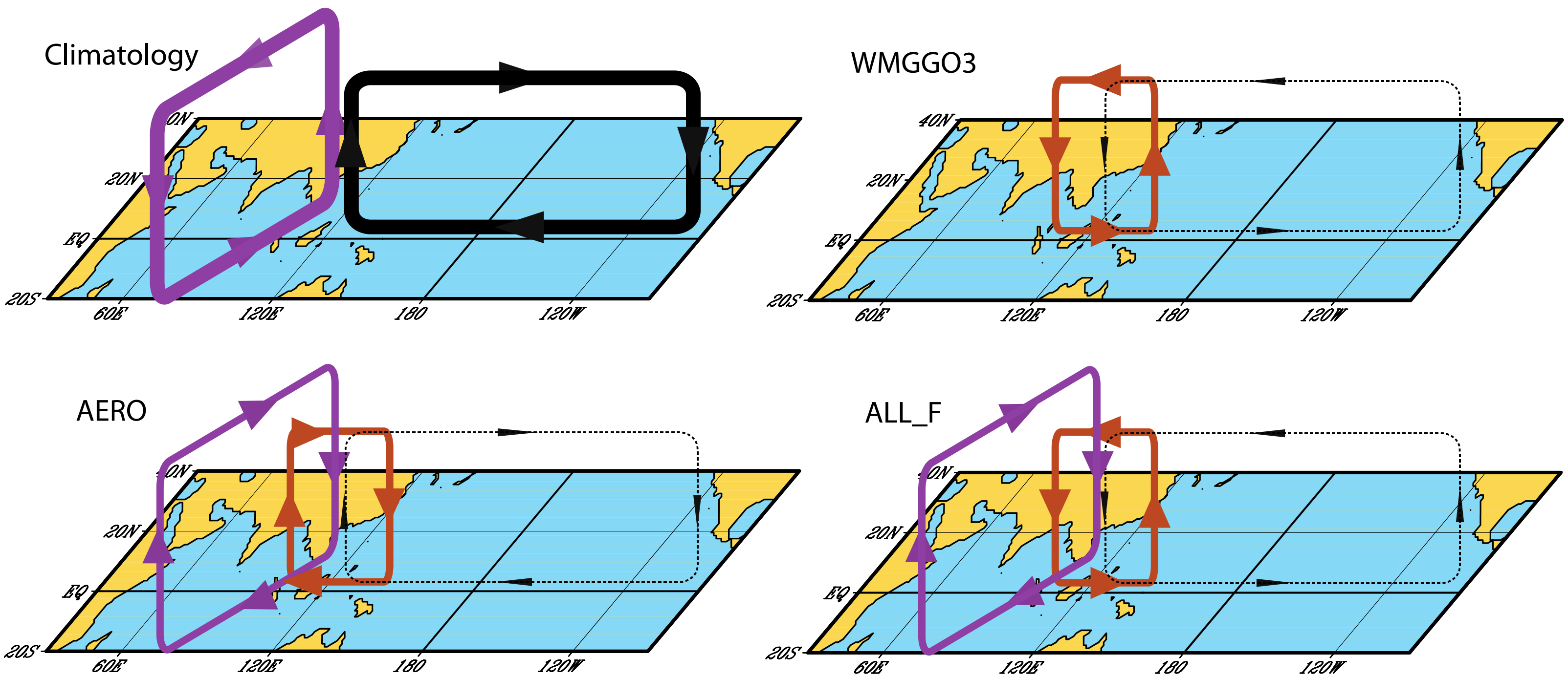
All forcing

GG

AERO

How Hadley and Walker circulations respond to greenhouse gases and aerosols?

Climatology **Greenhouse Gases**



Aerosols **All forcing**

How does the tropical heat engine response to aerosol forcing, and why?

From the viewpoint of atmospheric energy transport, the response gives rise to a cross-equatorial heat flux from SH to NH.