U.S. DEPARTMENT OF ENERGY

Uncertainties and Frontiers in Aerosol Research

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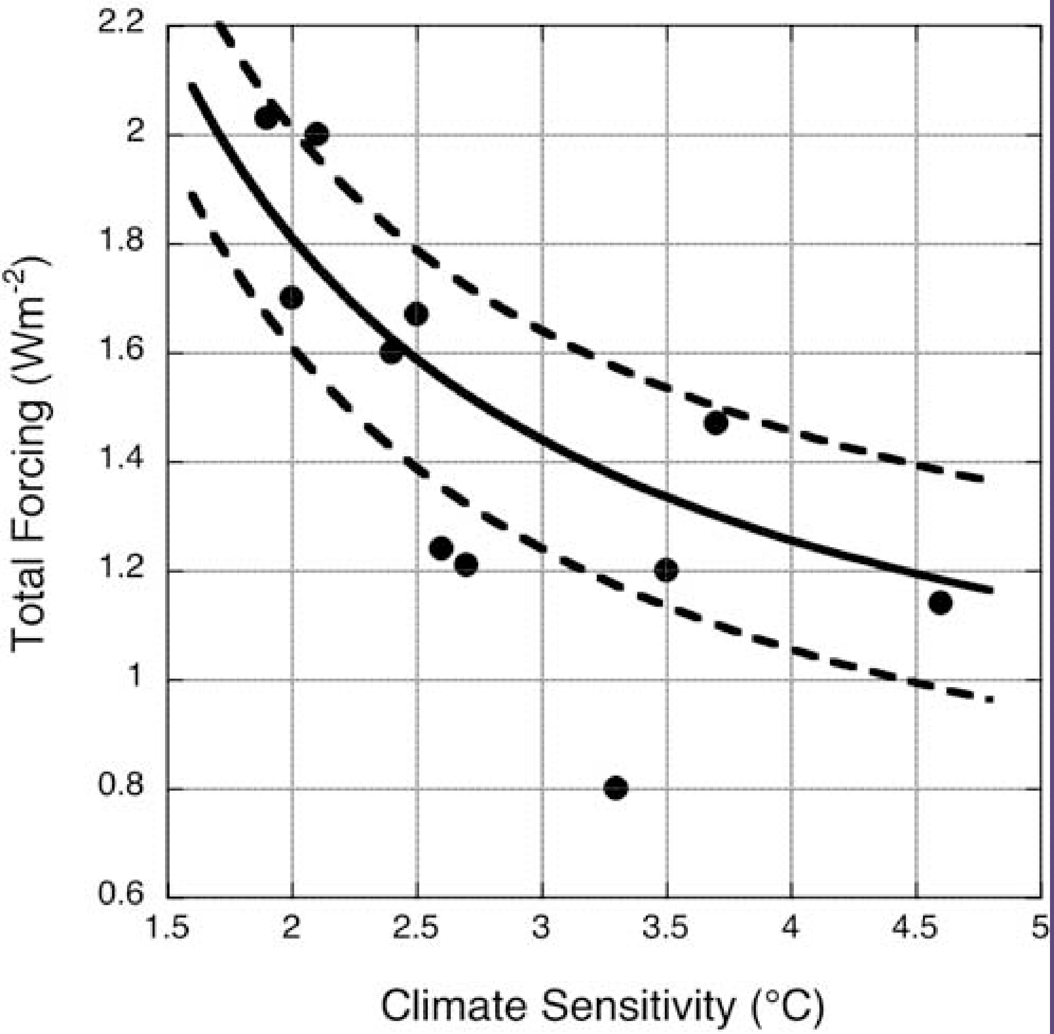
Aerosol Metrology for Climate Workshop March 14, 2011 NIST, MD

Outline

- Introduction: aerosol-climate effects
- 7 “hottest” research areas
- Agency activities

Anthropogenic aerosols have cooled the climate, by some amount…

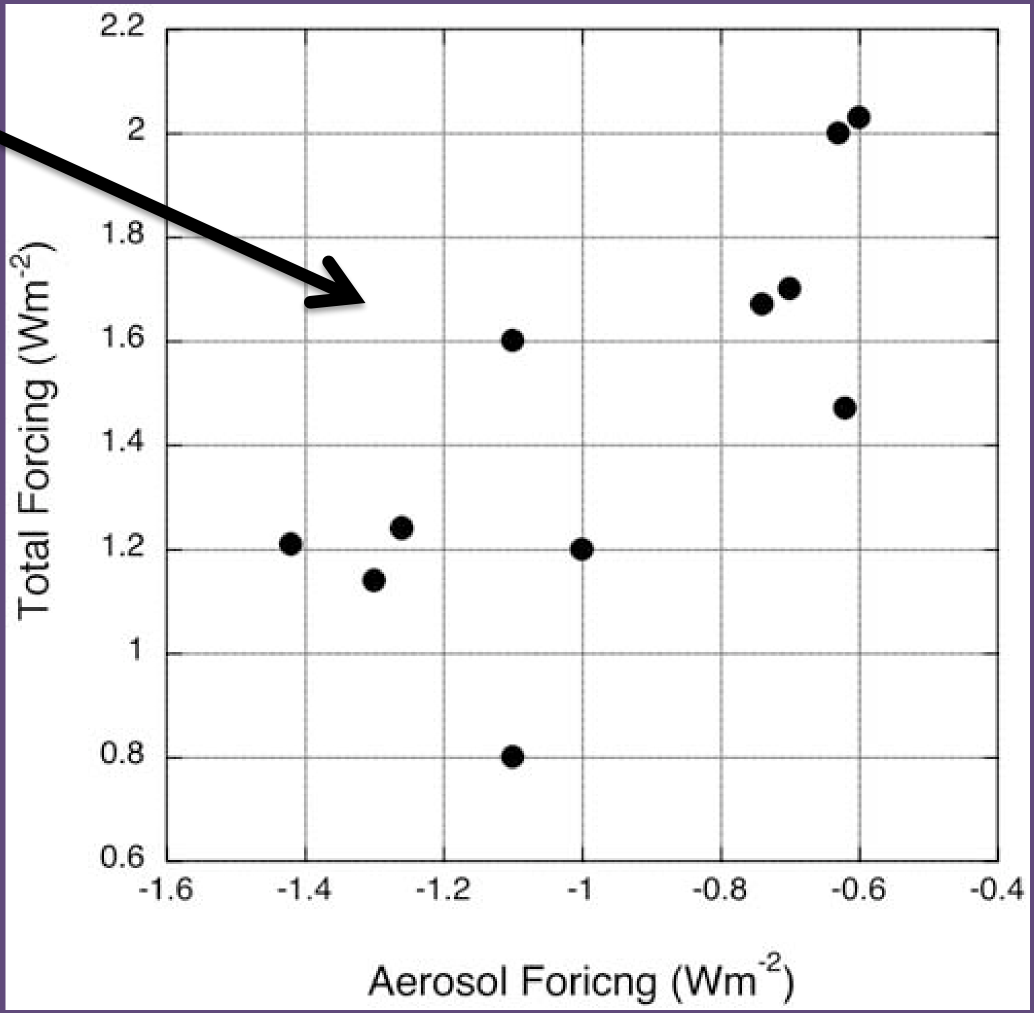


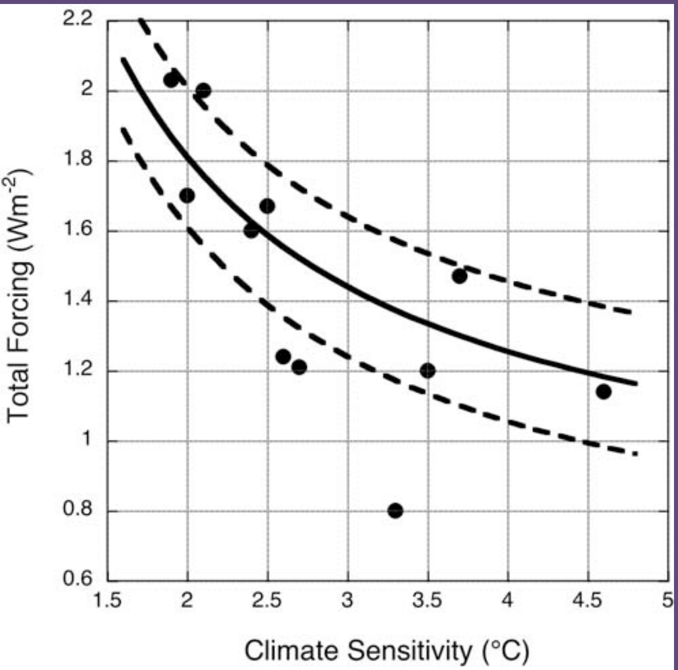
Amount of warming for doubled CO2

Kiehl (2007)
showed that AR4 climate models have smaller forcing if climate more sensitive…

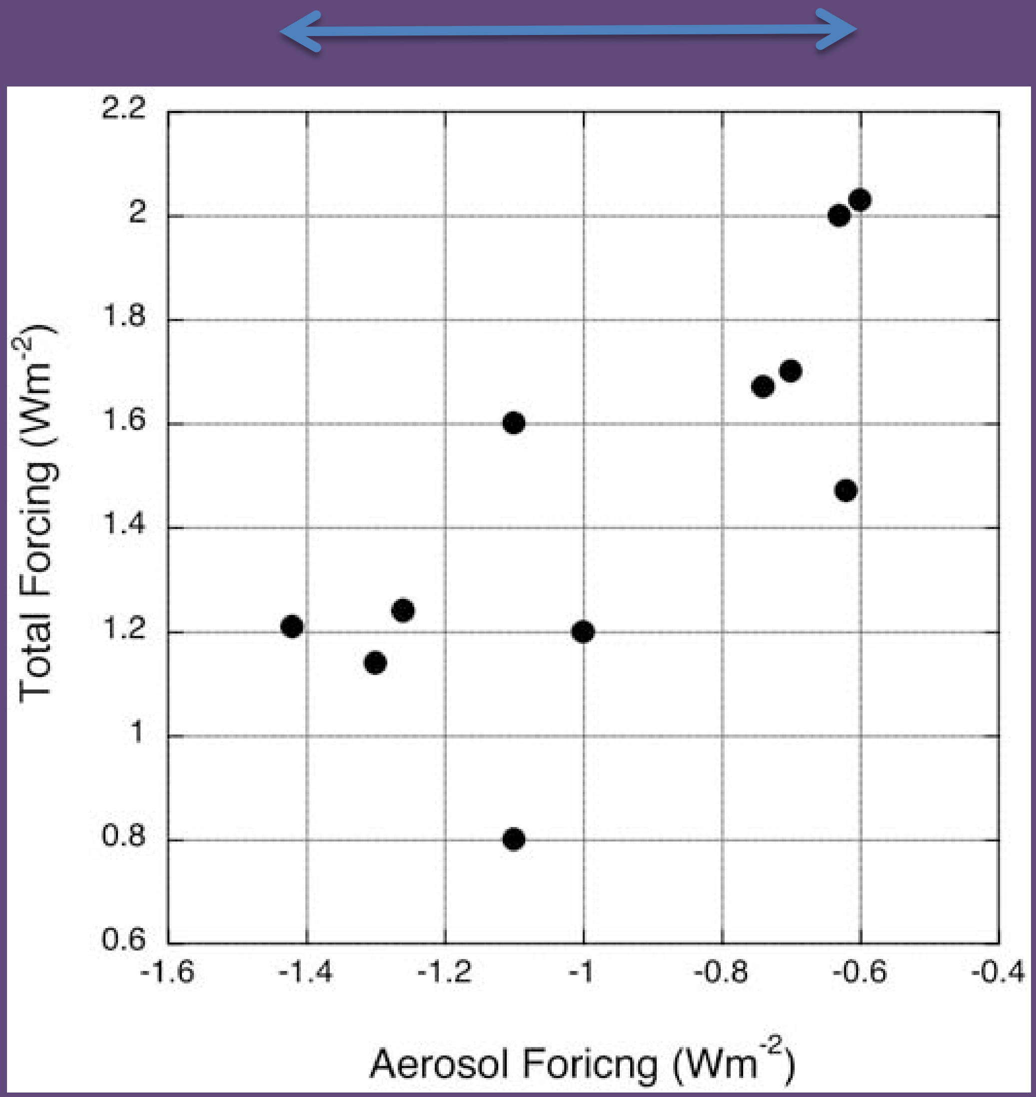
Model sensitivity

And most of the forcing difference is from aerosols



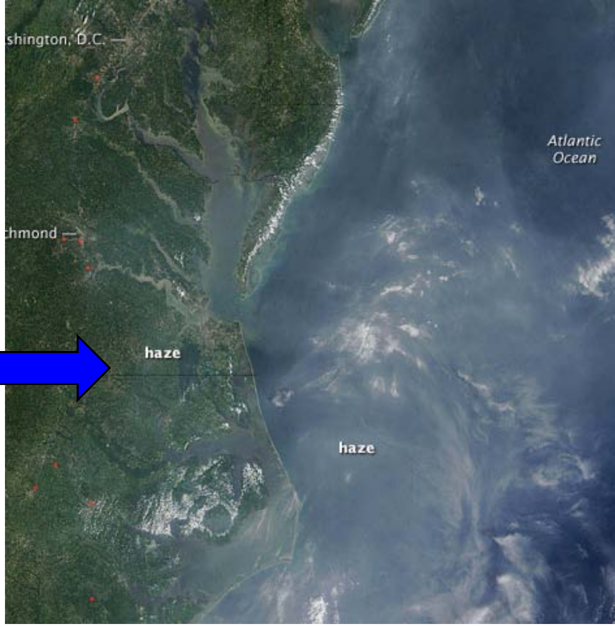


Aerosol uncertainty: about 1 Wm^{-2}



Aerosol Climate Effects

1. **"Direct" effects:** scatter, absorb incoming solar radiation. Sulfate, nitrate, organic carbon scatter. Black carbon (BC) also absorbs.

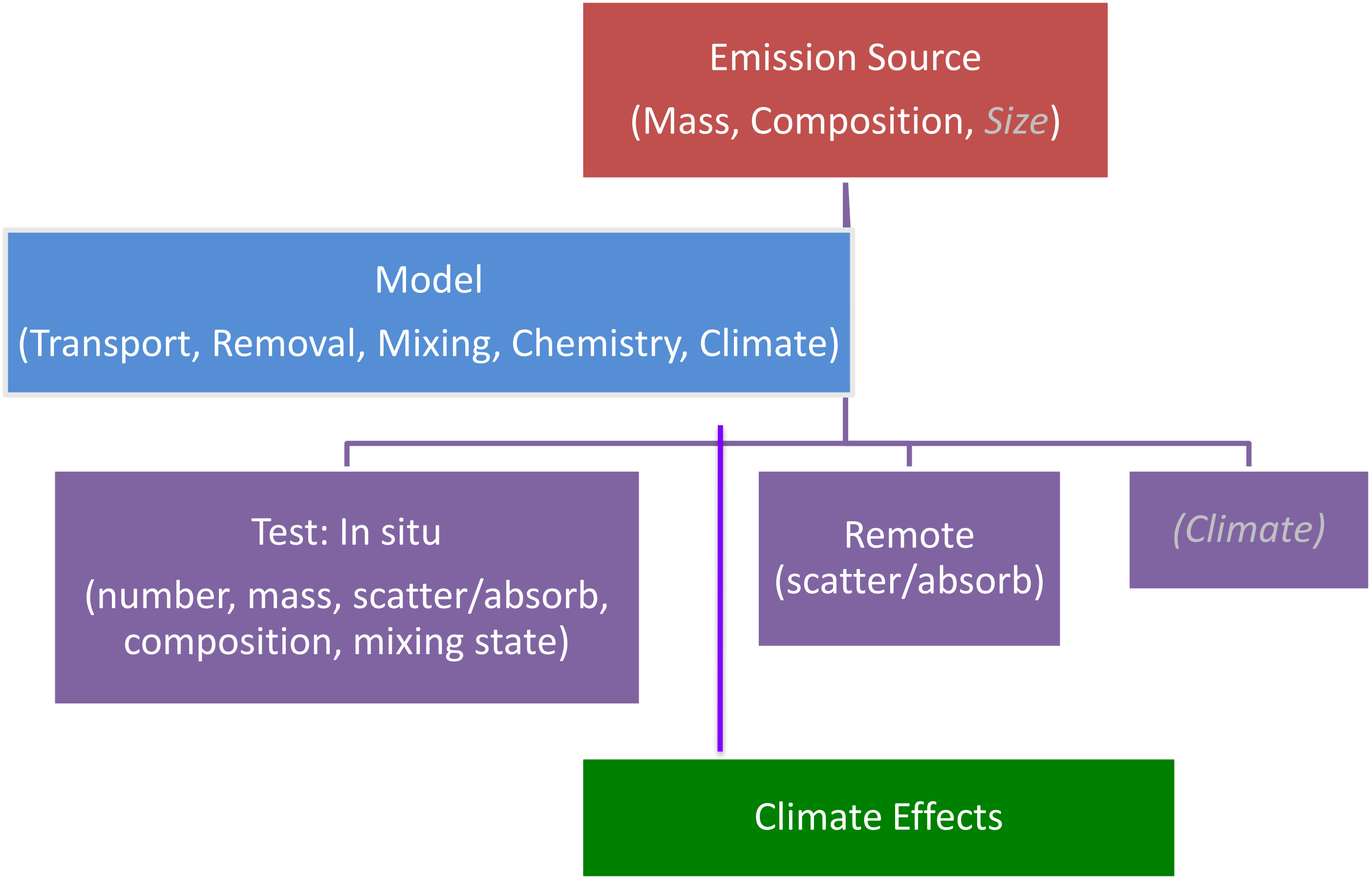


2. **Cloud micro-physical effects:** Aerosol pollution increases cloud droplet number, clouds brighter and longer-lived.

3. **Cloud macro-physical effects:** cloud response to change in atmospheric thermal structure

4. **BC-snow-albedo effect:** BC on snow reduces snow albedo, promotes melting

Aerosol research approach

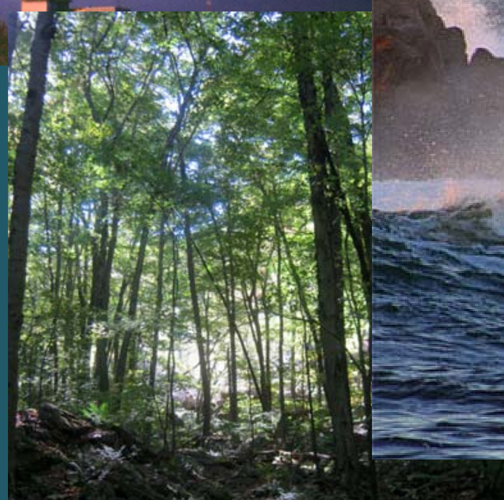


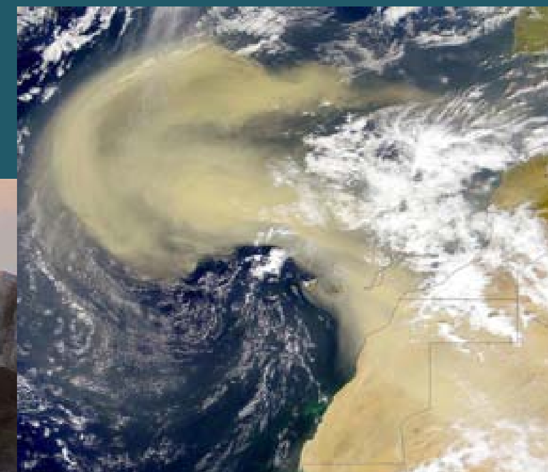
Resource: AeroCom, an international model intercomparison activity, since 2003
http://dataipsl.ipsl.jussieu.fr/AEROCOM/

Aerosols from pollution

Combustion of fossil fuel (coal, oil, diesel, gasoline), domestic wood burning, forest fires

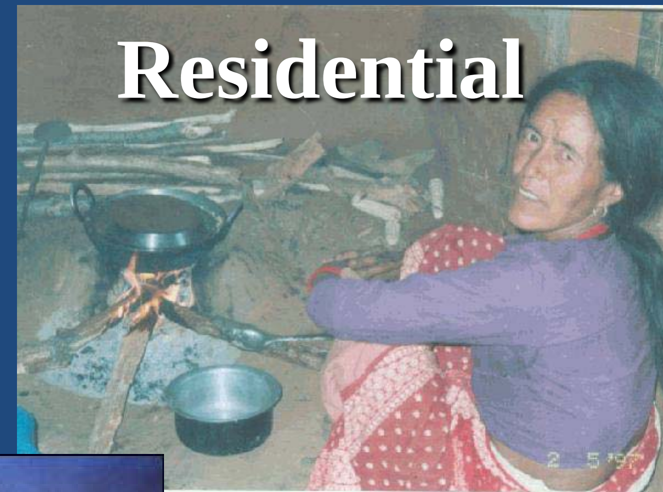
Natural sources of aerosols

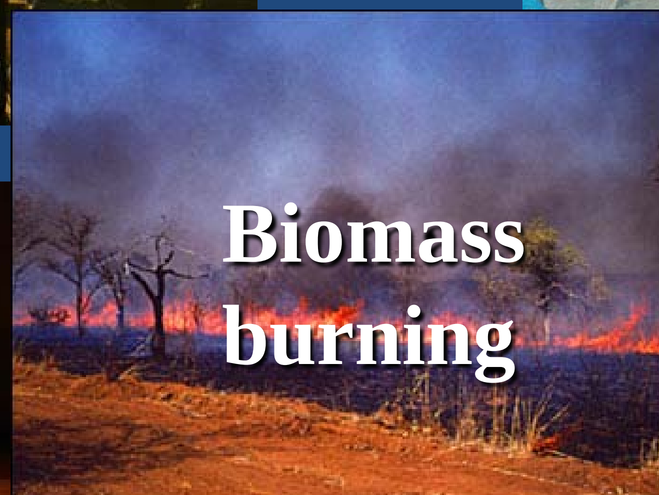




desert dust, sea salt, volcanoes, oceanic/terrestrial biological sources, natural fires

Human activity Perspective Aerosol Sources (rather than species)

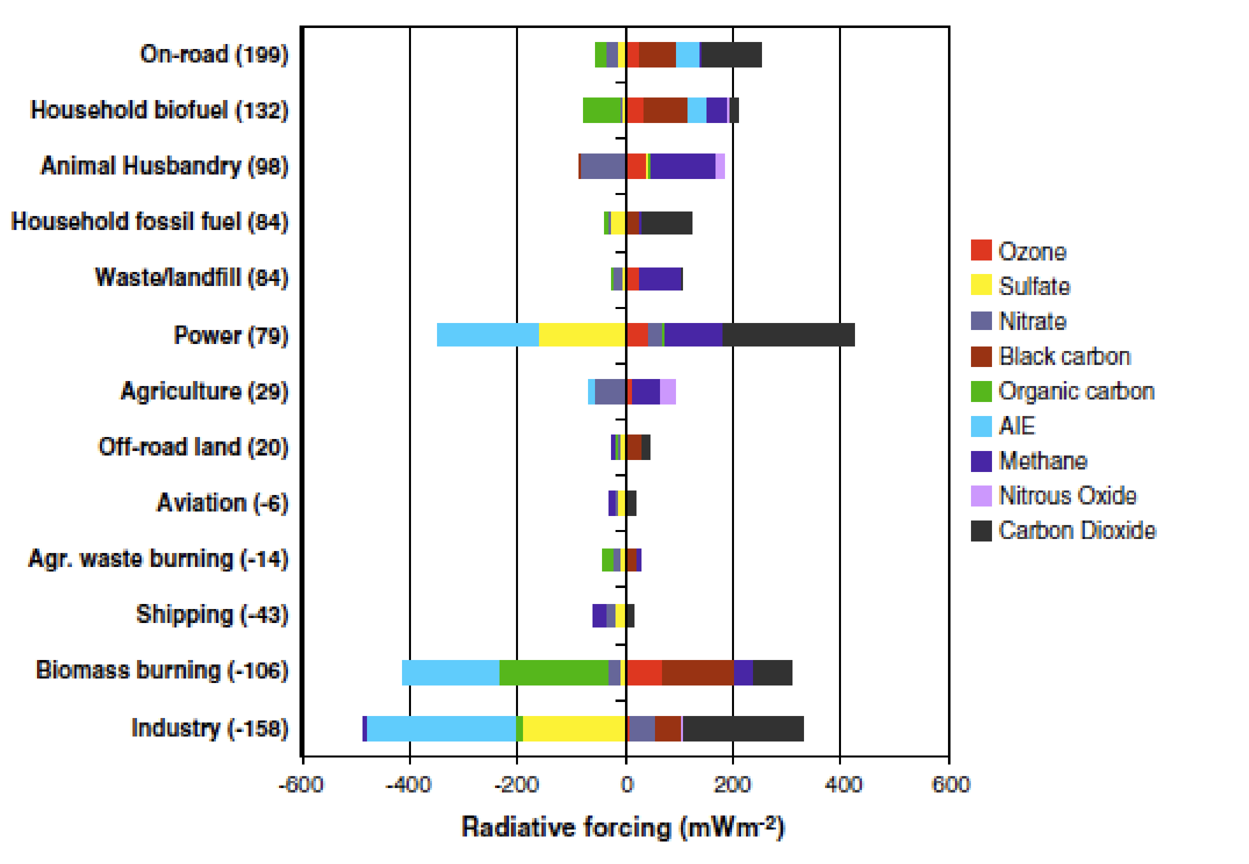




Aerosol Sector/Source Perspective

- Koch et al., *JGR*, 2007.
- Unger et al., *Proc. Natl. Acad. Sci.*, 2010.

Each sector, each source, generates its own cocktail of chemical species. Practically, the impact of e.g. sulfate or black carbon on climate is meaningless



#1 What is natural?

“Natural” aerosols: to what extent has human activity affected these?

desert dust, oceanic/terrestrial biological sources, natural fires, sea salt

#1

Vegetation changes

Pongratz et al., GBC, 2007

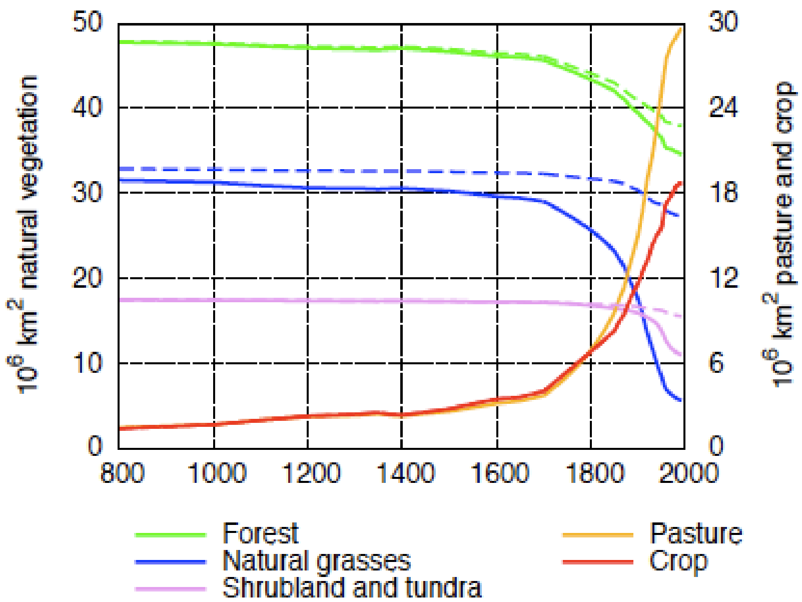
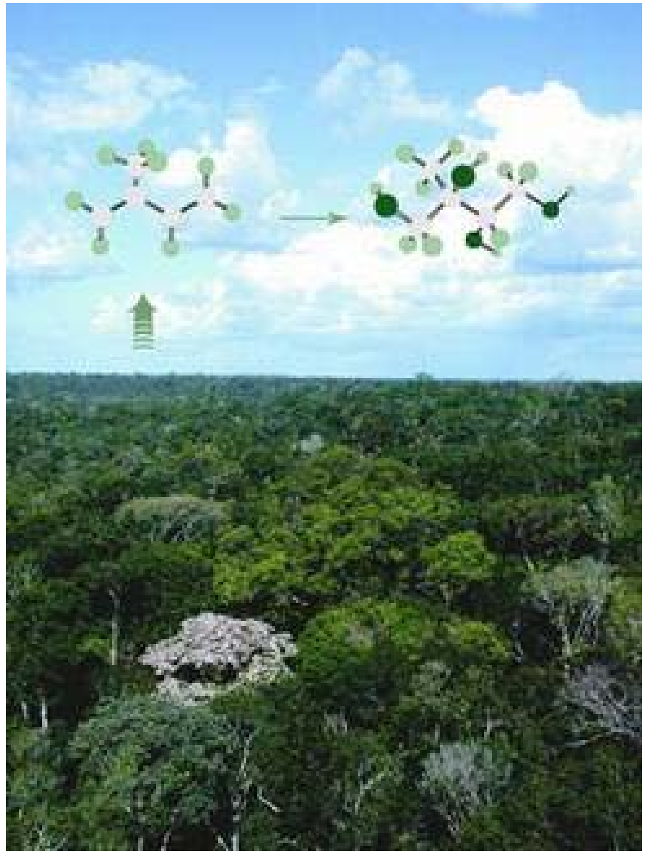


Figure 6: Global area of natural vegetation (left axes) and the land use types crop and pasture (right axes) from AD 800 to 1992 (in 10^6 km^2). Dashed lines are land cover change due to cropland only.



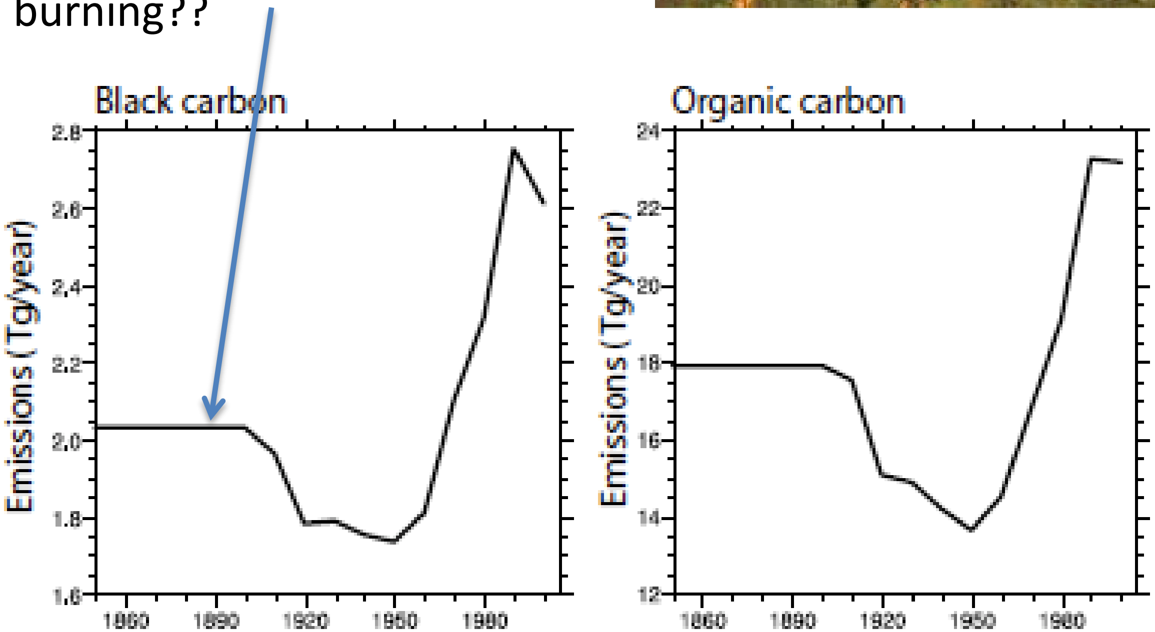
#1

Biomass burning

Emissions for AR5:

Substantial high-latitude burning

Land clearing implies burning??



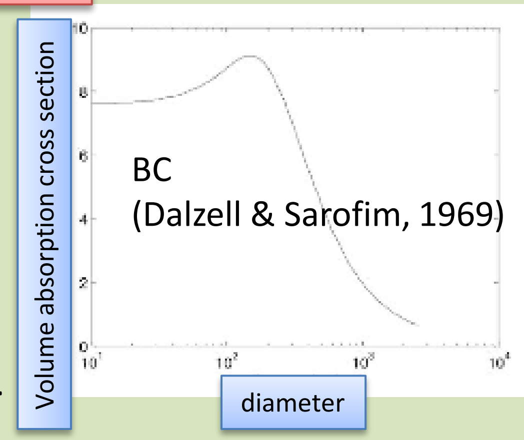
Aerosol uncertainties: about 1 Wm^{-2}

1. Aerosol sources, histories
   - What is natural: how have dust, burning, bio-sources changes?

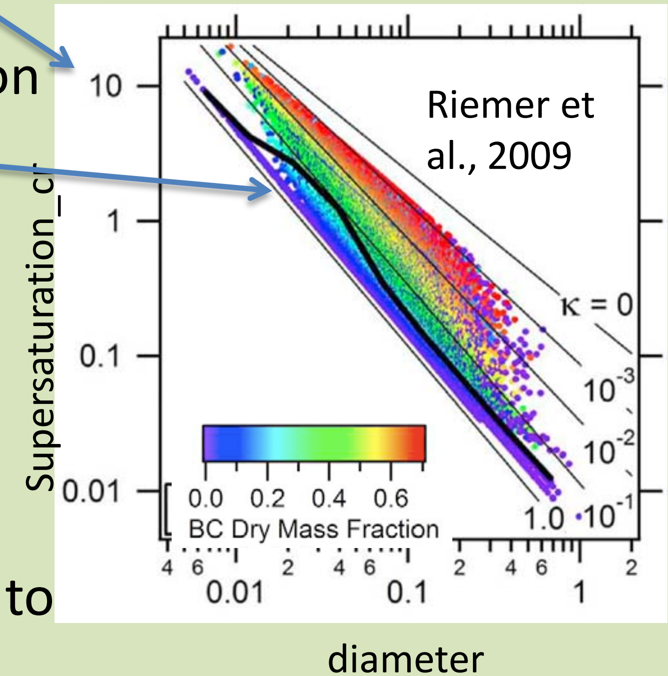
#2

Aerosol microphysics: size distribution, mixing state, *morphology, shape*

1. Size
   - optimal size for absorption
   - large particles better cloud/ice nuclei



2. Mixing state
   - BC absorption increases when mixed with non-absorbing material (Jacobson, 2000)
   - Affects particle hygroscopicity, ice nucleation potential



3. Shape
   - Important for direct effect, ice nucleation potential

Models now simulate #1, 2 (nucleation, condensation, coagulation) but only beginning to compare with field measurements

Aerosol uncertainties: about 1 Wm^{-2}

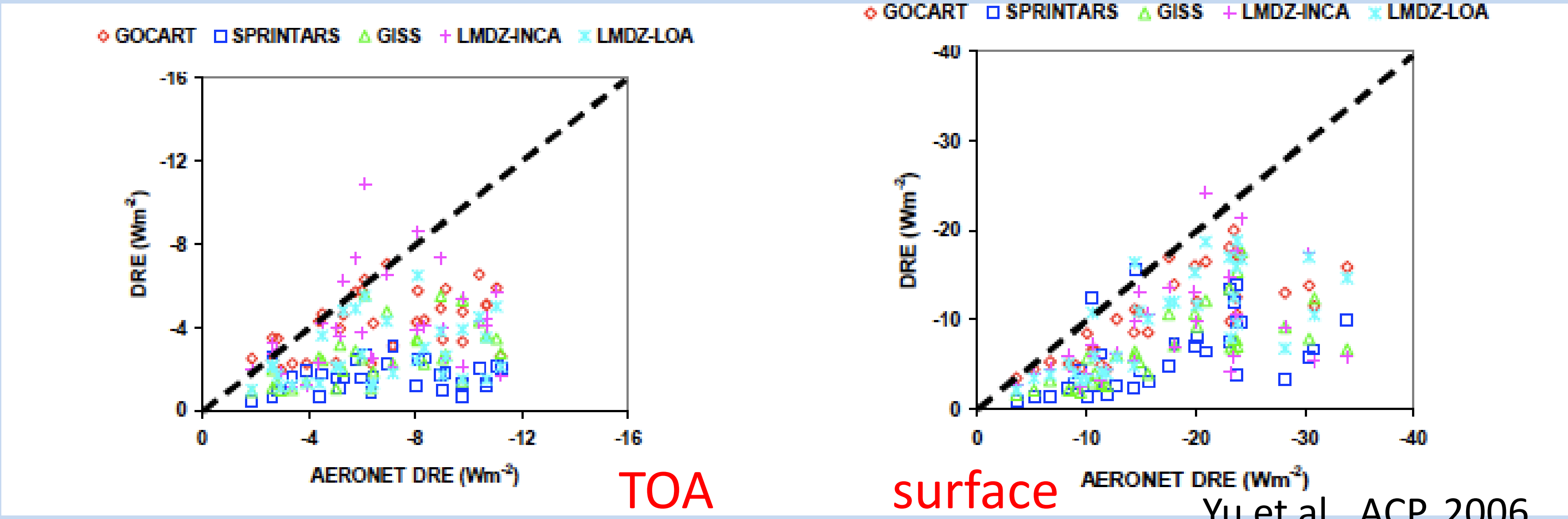
1. Aerosol sources, histories
   - What is natural: how have dust, burning, bio-sources changes?
2. **Aerosol size, mixing state, *shape*; Observed, modeled**

#3 Closure

Remote vs in-situ measures of aerosols

Emissions➔model, compare model to obs

- ✔Model ≅ Obs for in-situ (mass of most stuff)
- ✖ Model < Obs for aerosol optical depth (AOD), absorption aerosol optical depth (AAOD), direct radiative effects



Yu et al., ACP, 2006

#3

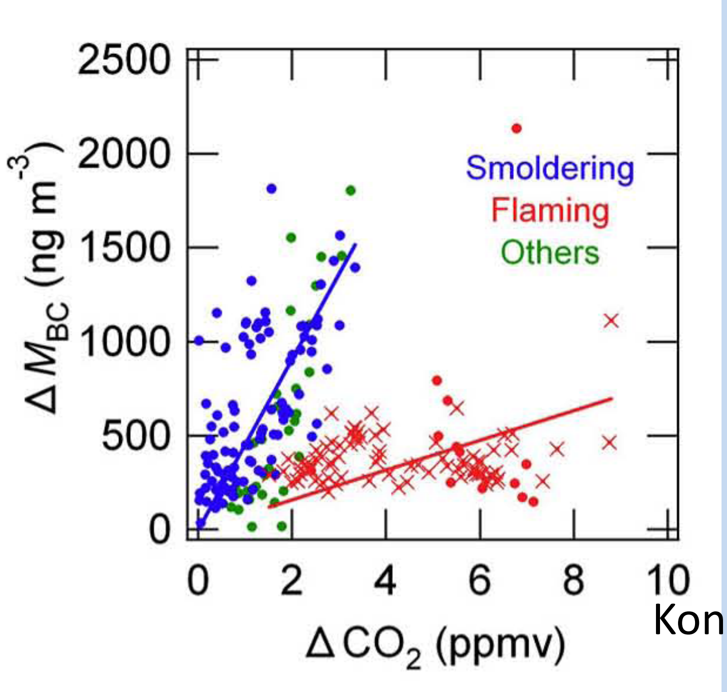
Closure: Remote vs in-situ measures of aerosols

Emissions➔model

- ✔Model ≅ Obs for in-situ mass
- ✖ Model < Obs for absorption aerosol optical depth (AAOD)

BC surface concentration, AAOD, ratio of model/observed, 15 models (Koch et al., ACP, 2009)

Average model biases	N Am	Eur	Asia	S Am	Afr	Rest
Surface concentration	1.6	2.6	0.50	NA	NA	1.4
AERONET AAOD	0.86	0.81	0.67	0.68	0.53	0.55
OMI AAOD	0.52	1.6	0.71	0.35	0.47	0.26



Biomass burning differences in BC

Asian

North American

Kondo et al., JGR, in press

#3

Closure: Remote vs in-situ measures of aerosols

Potential solutions (Myhre, Science, 2009):

1. Harmonize model diagnostics to observations ("simulators" for e.g. clear-sky, satellite overpass)
2. Aerosol microphysics in models (increases absorption)
3. Source deficiencies (biomass burning, Asia)
4. Missing organic aerosols

Aerosol uncertainties: about 1 Wm^{-2}

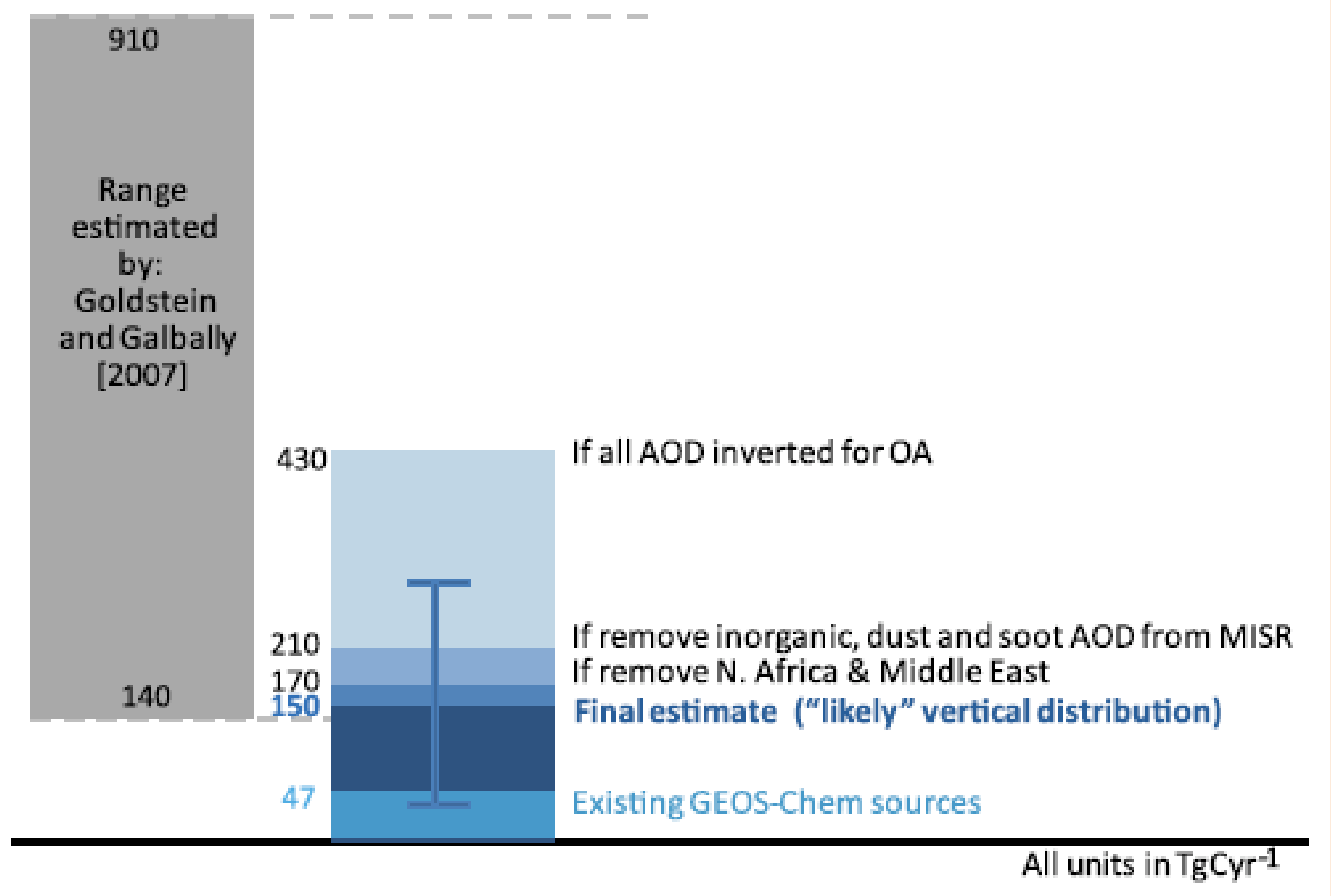
1. Aerosol sources, histories
   - What is natural: how have dust, burning, bio-sources changes?
2. Aerosol size, mixing state, *shape*; Observed, modeled
3. **Closure (remote vs in-situ)**

#4 Organic aerosols

- Pollution/burning: mostly primary (organic) particles
- Biological: mostly secondary
- Less than ½ of organics have been identified

Heald et al, GRL, 2010

Comparing forward model with MISR satellite retrieval ➔ model needed about 3x OA source used in model



Organic aerosols

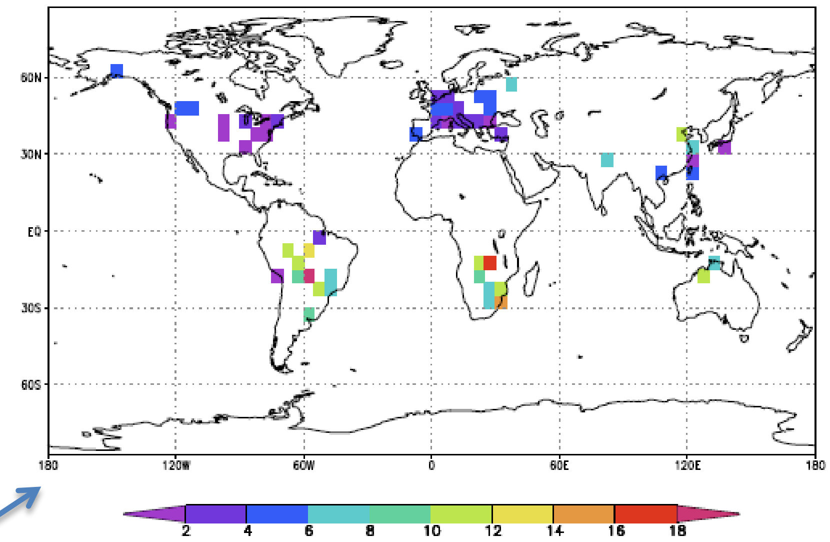


Fig. 2. Mean absorbing OC concentration (mg m^{-2}) inferred from AERONET-retrieved imaginary indices for September.

Arola et al., ACP, 2011

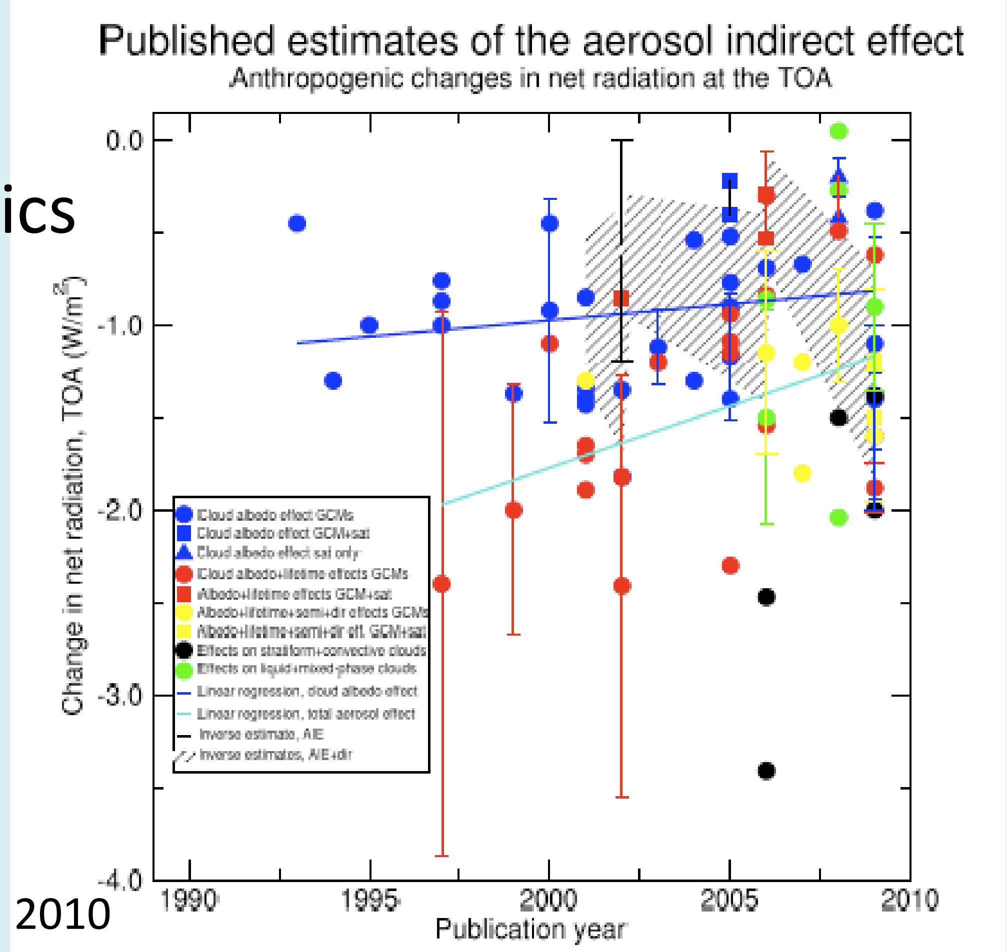
- Vary in hygroscopicity
- Vary in volatility
- Vary in absorption ("brown carbon")
- Potentially big impact on aerosol-cloud effects: particle number and hygroscopicity (Liu and Wang, *Env Res Lett*, 2010: -1.3±0.4 Wm^{-2})
- Some global models now have (simple) SOA chemistry, beginning to compare with observations

Aerosol uncertainties: about 1 Wm^{-2}

1. Aerosol sources, histories
   - What is natural: how have dust, burning, bio-sources changes?
2. Aerosol size, mixing state, shape; Observed, modeled
3. Closure (remote vs in-situ)
4. **Organic aerosol sources, load, optical properties, hygroscopicity**

#5 Aerosol-cloud effects

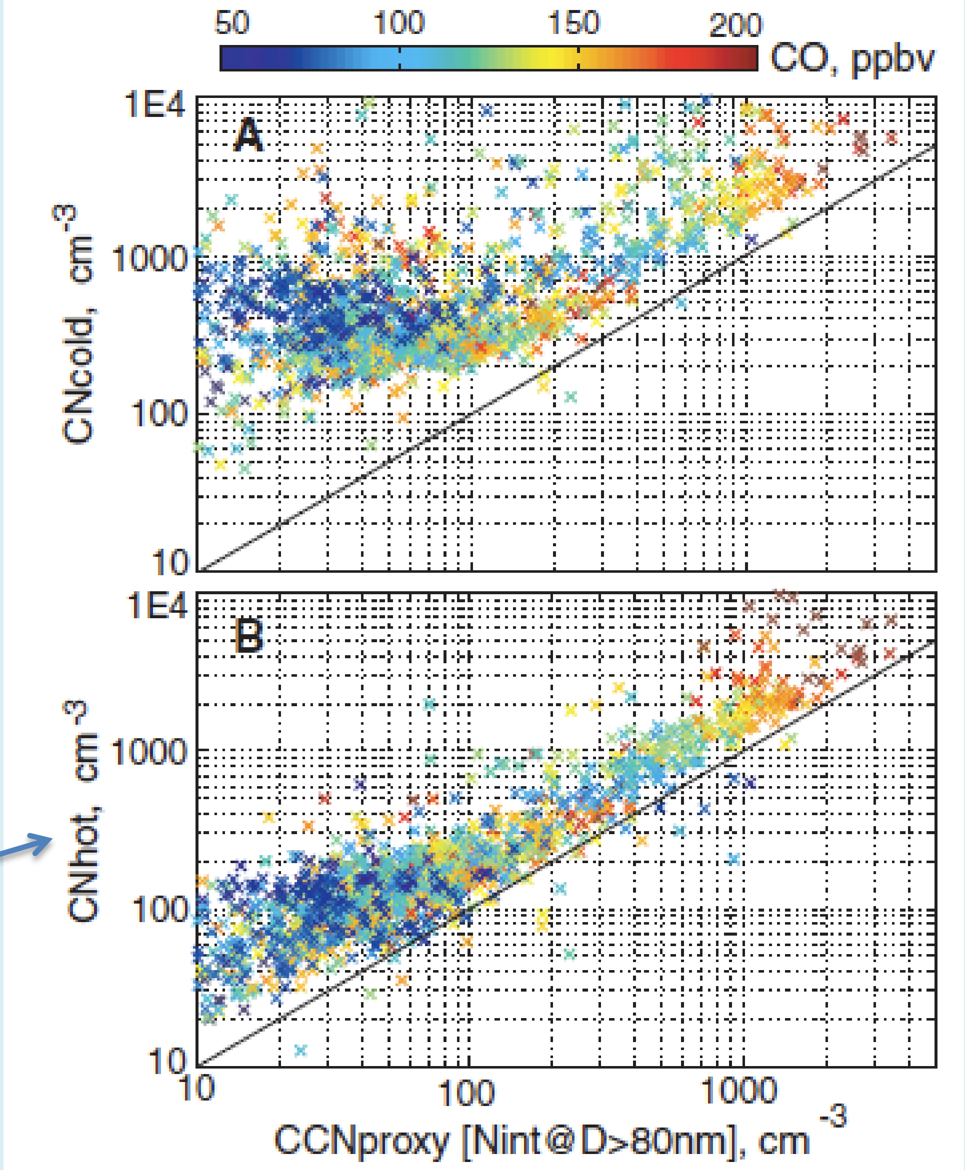
1. **Liquid cloud microphysics: Enhancement of cloud condensation nuclei (CCN) and droplet number ("indirect effect")**
2. Ice cloud microphysics
3. "Semi-direct effects"
4. Convective cloud dynamics



Lohmann et al., ACP, 2010

1. Aerosols enhance liquid clouds (cool)

Aerosol activation to a cloud droplet: depends on its **size** and **composition (hygroscopicity)**



Refractory particles (soot) correlate with CCN

Clarke et al., Science, 2010

#5

2. Aerosols alter ice clouds

Ice clouds (cirrus) are warming.

Aerosol pollution impact *may be to increase or decrease* ice number

Soot *might* act as Ice Nuclei (IN):

1. Laboratory evidence is weak
2. Field evidence suggests role: enhanced soot in ice particles

Particle size/shape/morphology matters: Big, large aspect ratio is good IN (dust)

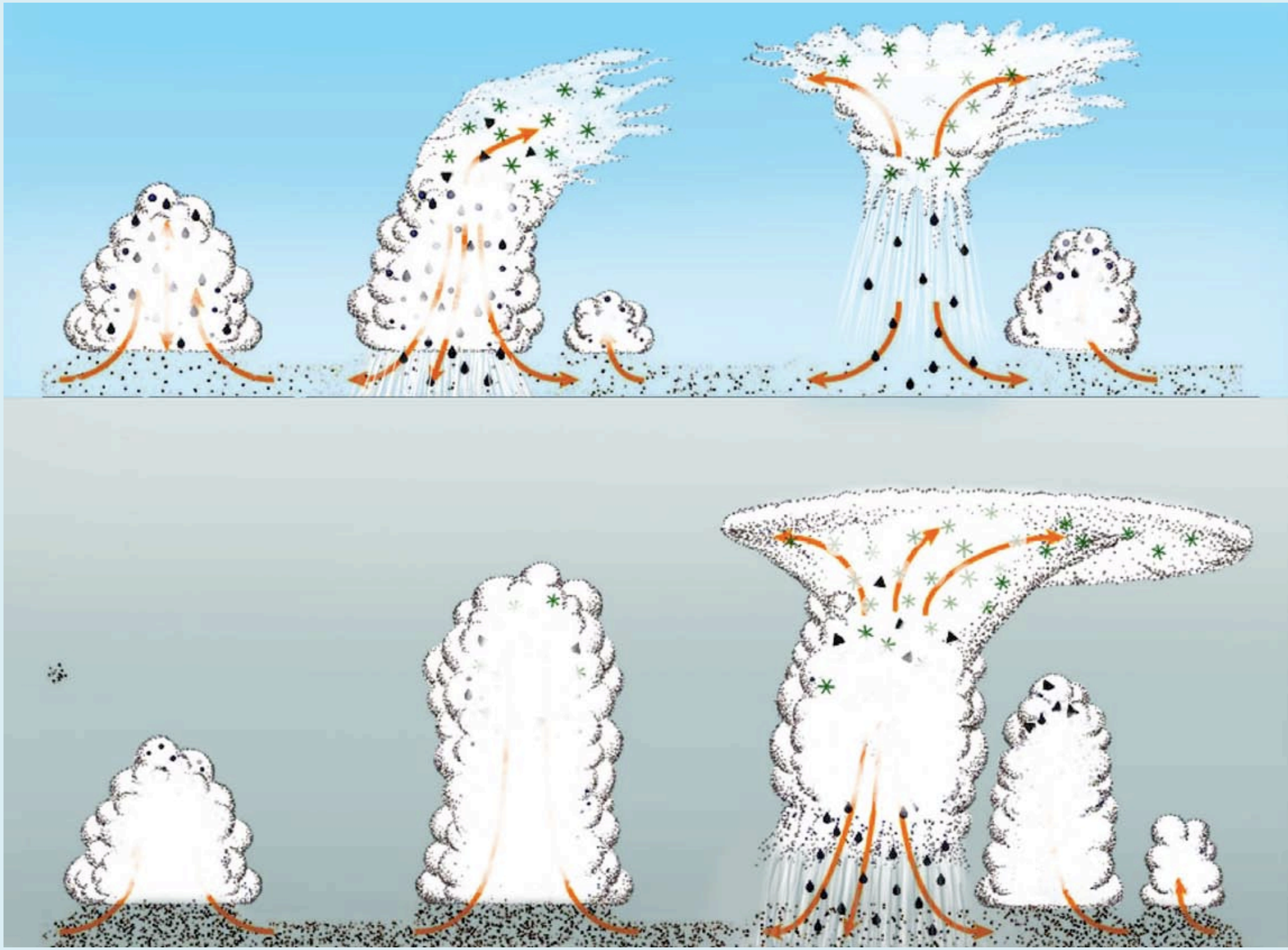
#5

3. Intensification of deep convection

Clean: larger drops rain sooner

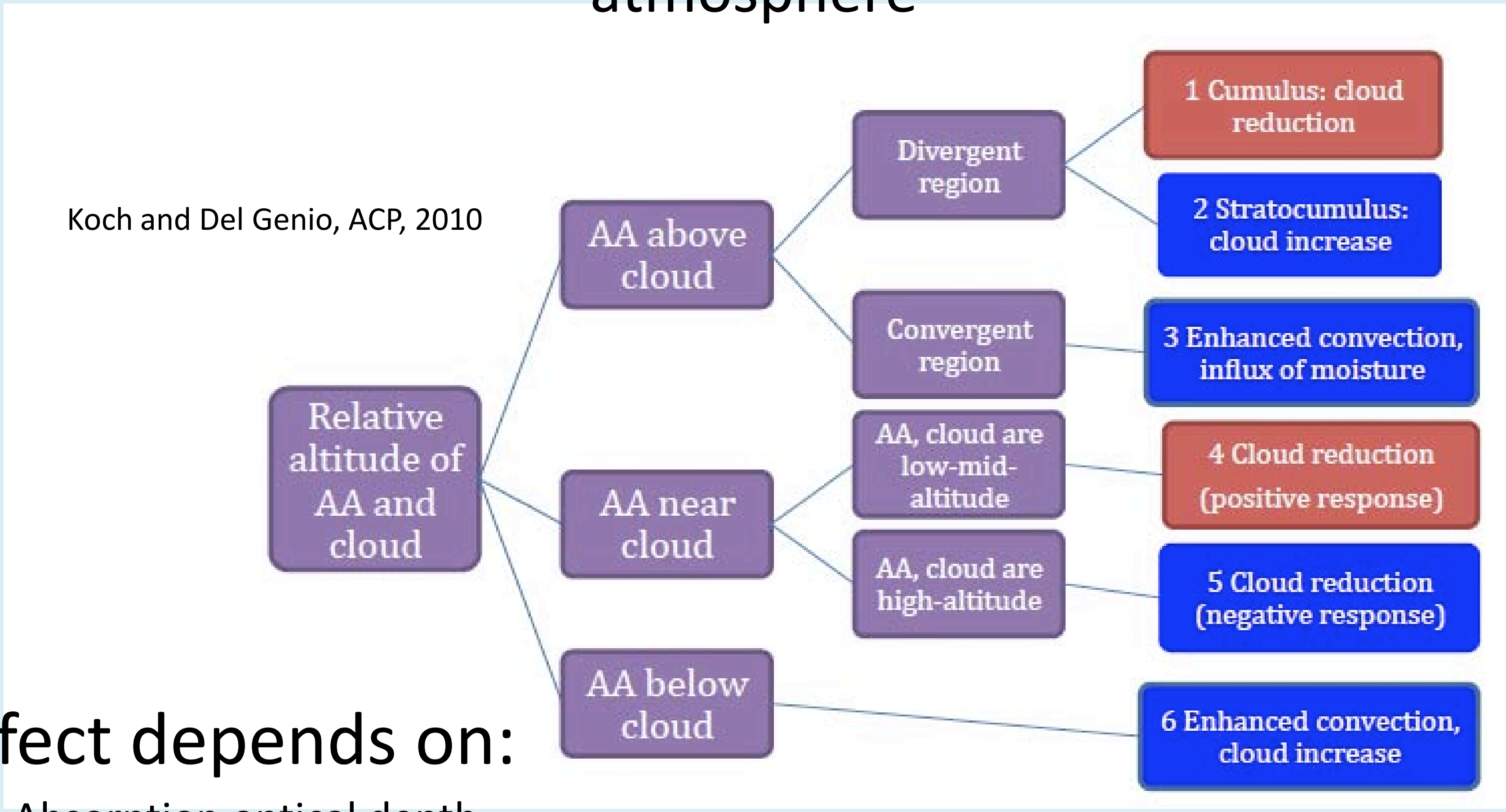
Polluted: smaller droplets, precip delay, clouds deepen and intensify

(Rosenfeld et al., Science, 2008)



#5

4. Absorbing aerosols (AA) alter thermal structure of atmosphere



Effect depends on:

- Absorption optical depth
- Altitude of aerosol
- Dynamical and hydrological conditions

Coordinated (field + cloud-scale model + global scale model) studies needed

Aerosol uncertainties: about 1 Wm^{-2}

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2. Aerosol size, mixing state, shape; Observed, modeled
3. Closure (remote vs in-situ)
4. Organic aerosol load, optical properties, hygroscopicity

5. a. Warm cloud: validation of aerosol microphysical models

b. Ice clouds: role of soot-cloud effects in situ

c. Thermal atmospheric changes: coordinated field-model study

#6

Black carbon mitigation to cool climate: BC suspended in atmosphere, deposited on snow are warming. Because of short lifetime, climate response to reduction is rapid

- IGAC: “Bounding the Role of Black Carbon on Climate” (Bond, Fahey, Forster, Doherty, et al.)
- UNEP: “Impacts and mitigation potentials of Ozone and Black Carbon” (Shindell, Ramanathan, Raes et al.)
- EPA: Report on the climate effects of BC
- Arctic council: task force on how to reduce global BC production

#6

BC-climate uncertainties

- BC is never "pure", it comes with organic carbon (biofuels), SO2 (fossil fuels). Must consider impact of sources, not just the BC. (e.g. diesel)
- BC-OC (soot) plays an important CCN (cloud-seeding) role which is cooling (e.g. Chen et al., 2010; Bauer et al., 2010; Koch et al., 2011)
- BC absorption may enhance low-level clouds in some regions (e.g. Koch and Del Genio, 2010)
- BC impacts on ice-clouds poorly understood

#6

BC-climate uncertainties

Aerosol uncertainties: about 1 Wm^{-2}

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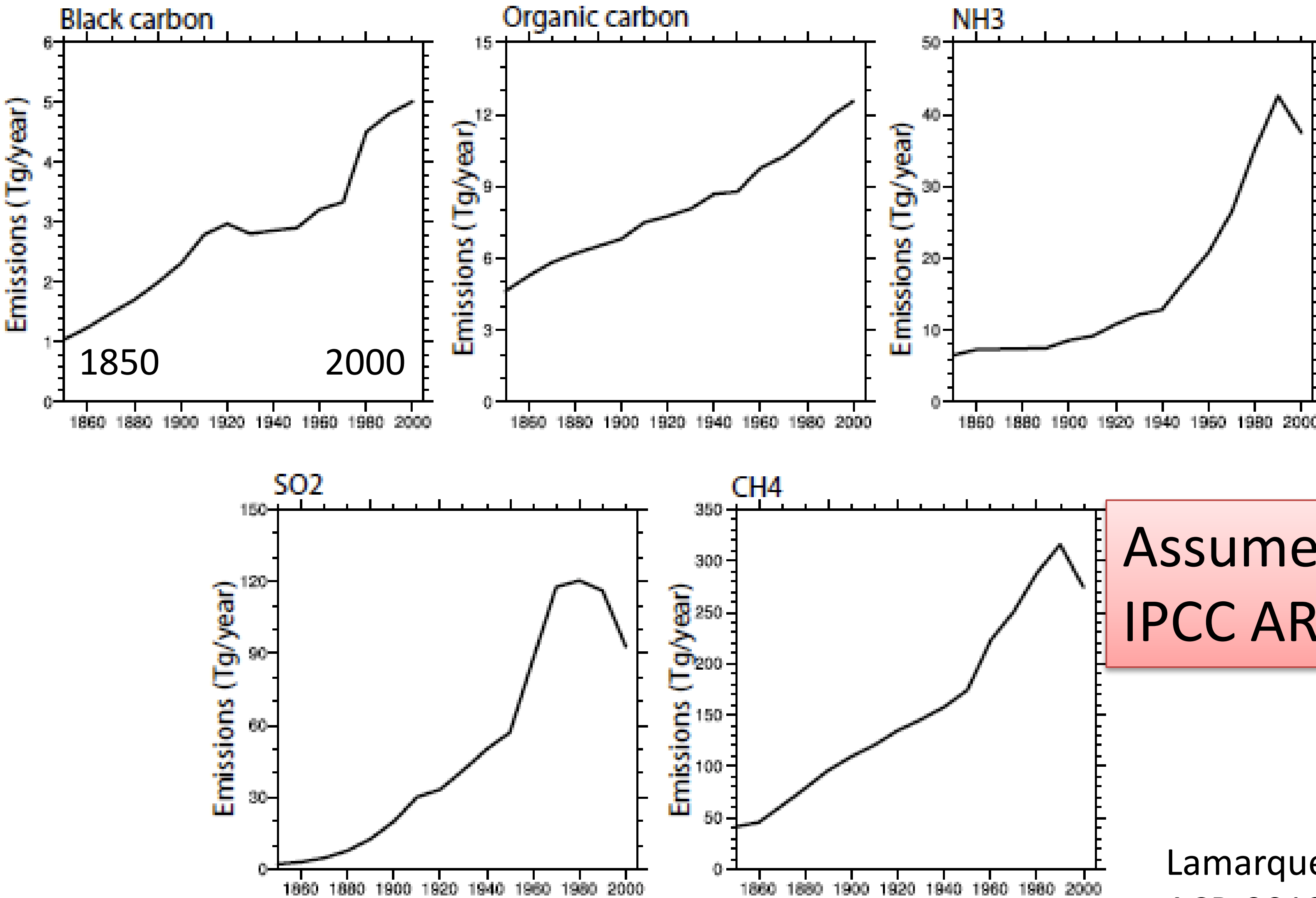
   c. Thermal atmospheric changes: coordinated field-model study
6. **BC mitigation potentials (how warming is BC + co-emitted species?)**

Aerosol pollution: complex, uncertain history

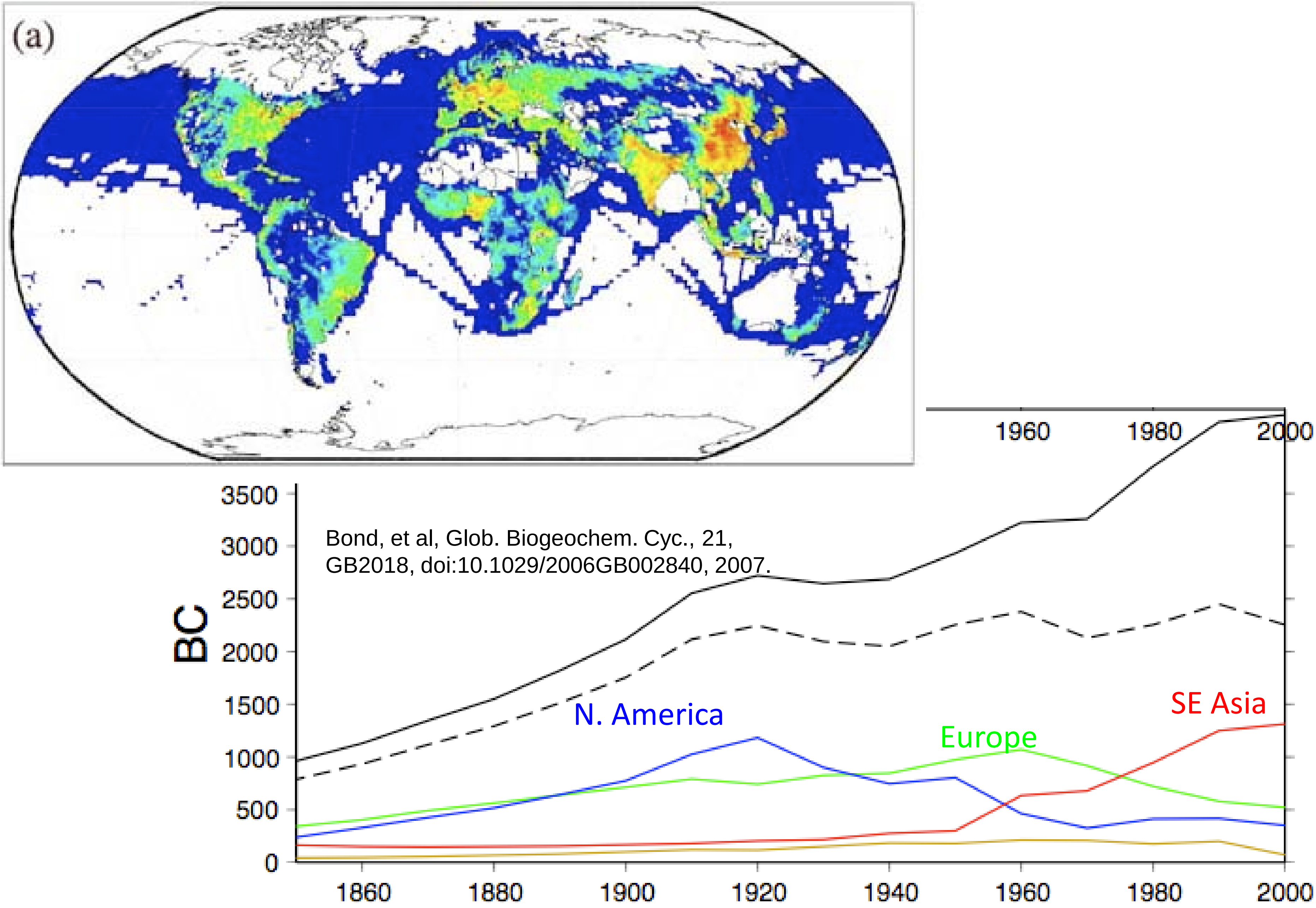


Assumed for IPCC AR5

Lamarque et al., ACP, 2010

However these are very heterogeneous in space-time

For example, black carbon emissions

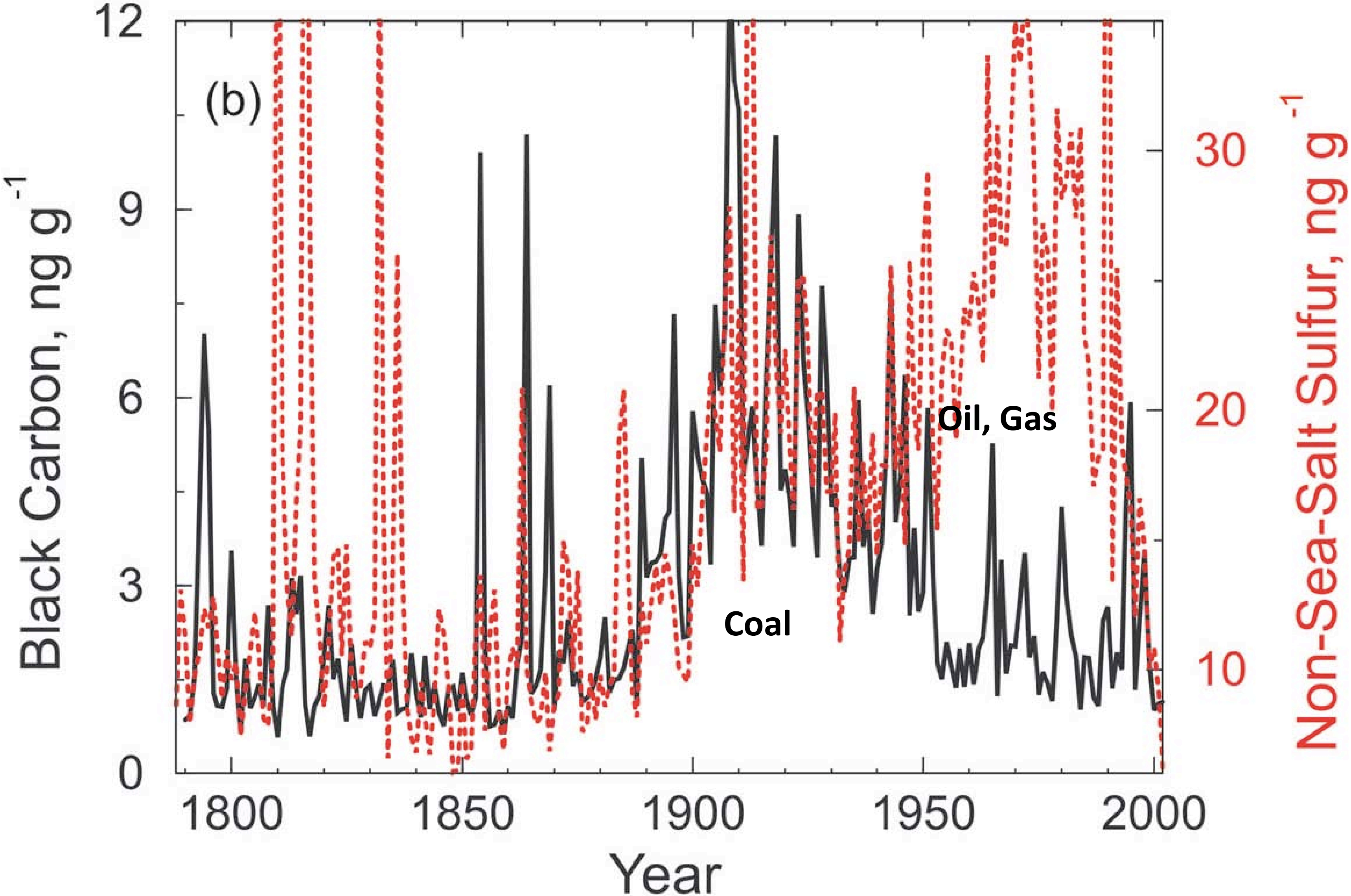


#7

Greenland ice core records

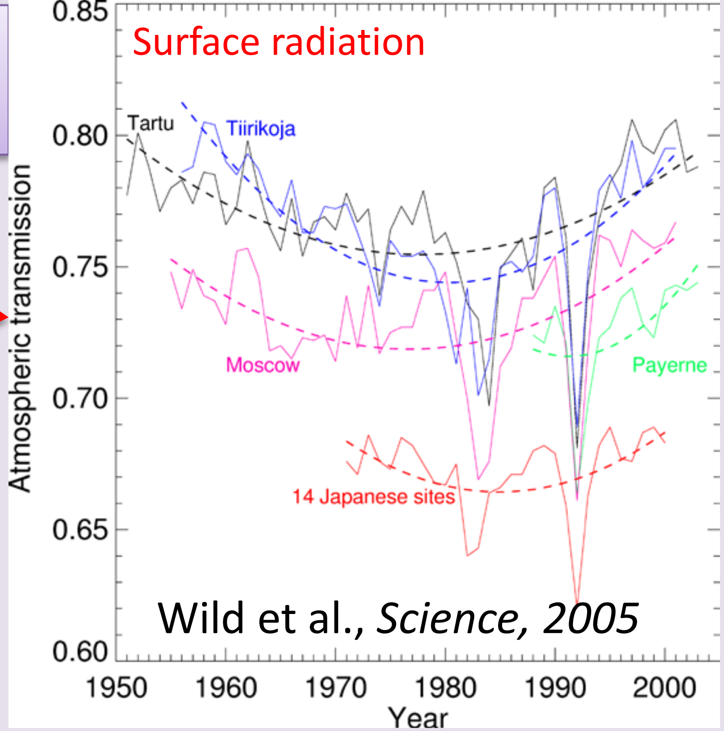
McConnell et al., 2007

Indicator of North American pollution changes



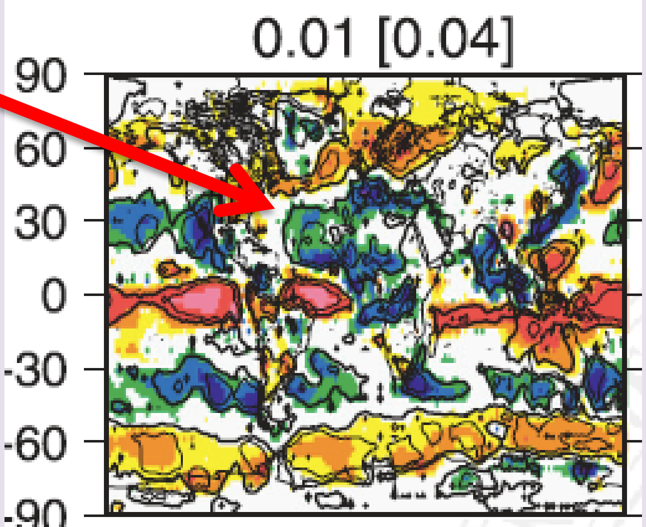
#7 Historical aerosol-climate effects

- Dimming/brightening (models underestimate)
- Southward shift of ITCZ due to more cooling from aerosols in NH (e.g. Takemura et al. 2005; Rotstayn et al. 2000; Zhang et al. 2007; Koch et al., 2011; Chang et al., 2011), contributed to drought over West Africa
- Hydrologic slowing (precipitation suppression) even from absorbing aerosols (Ming et al., GRL, 2010)



Wild et al., *Science, 2005*

Change in precip over 20th century



Koch et al., J Clim, in press

Aerosol uncertainties: about 1 Wm^{-2}

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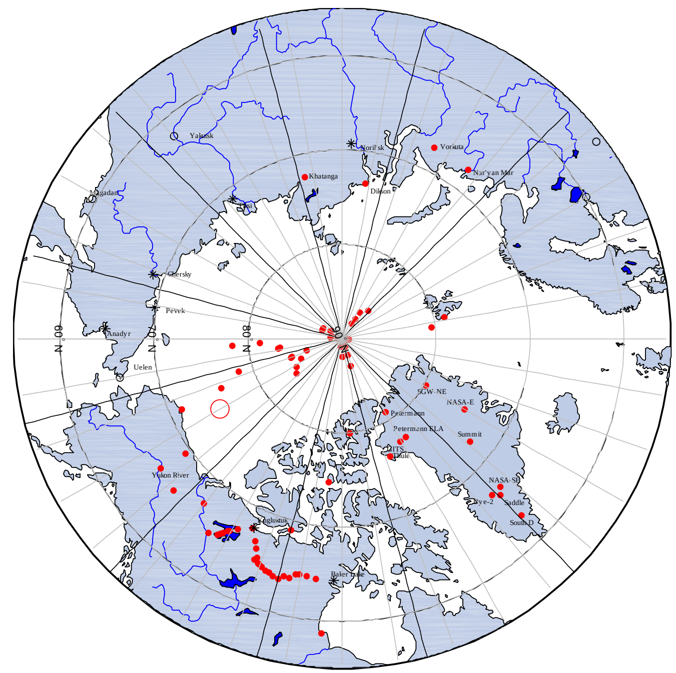
6. BC mitigation potentials (how warming is BC + co-emitted species?)

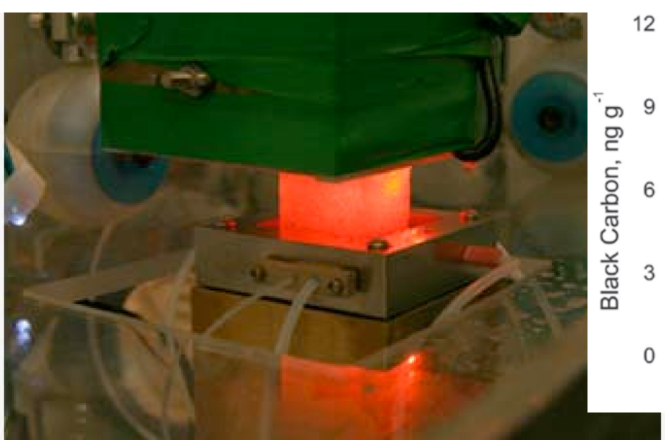
7. Detangling aerosol historical impacts on climate

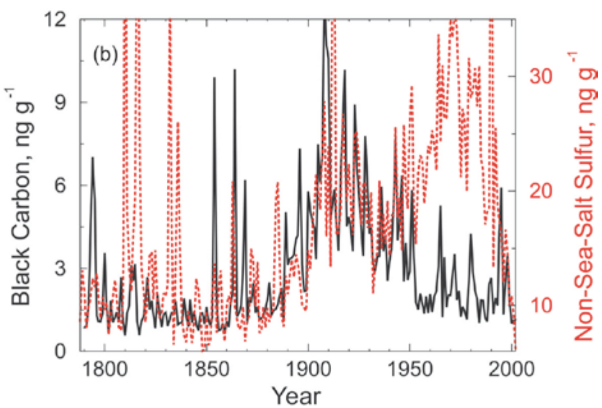
National Science Foundation
WHERE DISCOVERIES BEGIN

- Laboratory, field, modeling activities
- Milagro field campaign(2006): Evolution of pollution from Mexico City
- BC-on-snow (Warren, Grenfell, et al)
- Ice core records of aerosols (e.g. McConnell, Ross, et al)

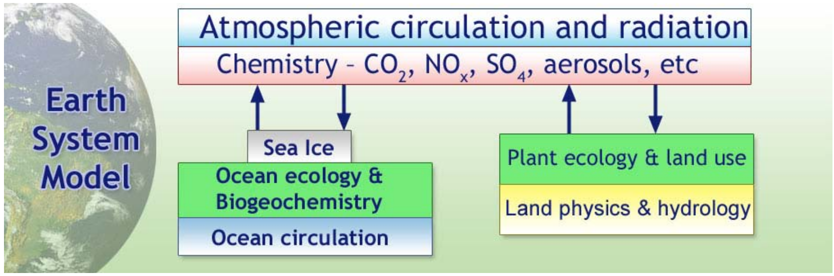


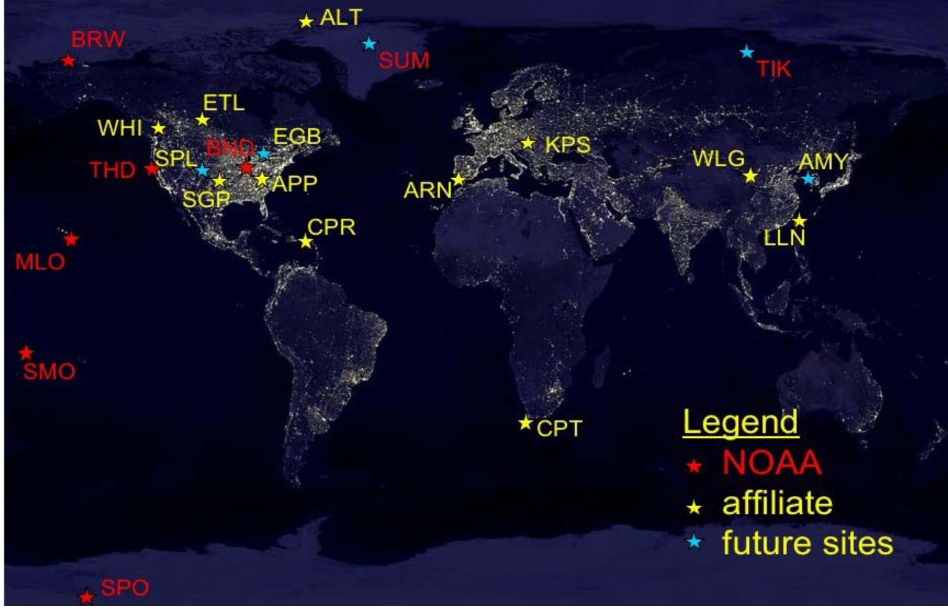
Ice Core records in Greenland, Arctic, Antarctic





- GFDL model





- Monitoring sites: http://www.esrl.noaa.gov/gmd/aero/net

Nephelometer, Particle Soot Absorption Photometer, Condensation Nuclei Counter

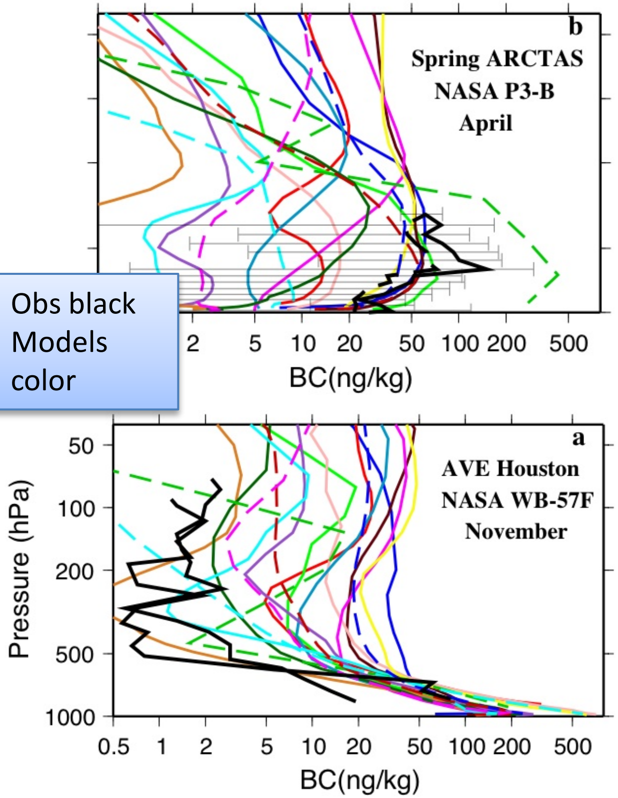
(optical properties, CCN, chemistry, f(RH), Angstrom exponent, size distribution)

- Field studies with aircraft and ships

BC measurements: SP2 Particle Soot Photometer

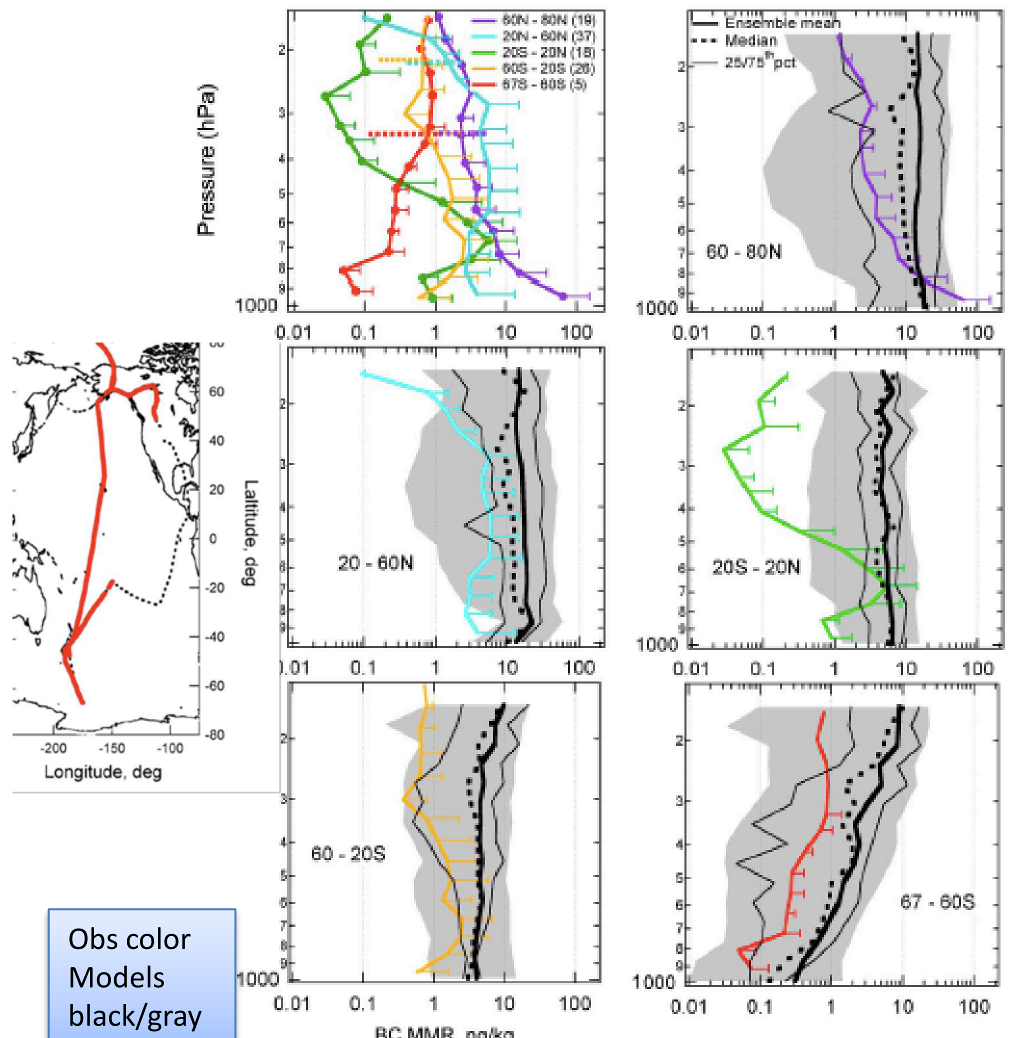
E.g. Aircraft: Schwarz et al., GRL, 2010; Koch et al., ACP, 2009
Also in ice cores McConnell et al., 2007

North America



Obs black
Models
color

Pacific Ocean



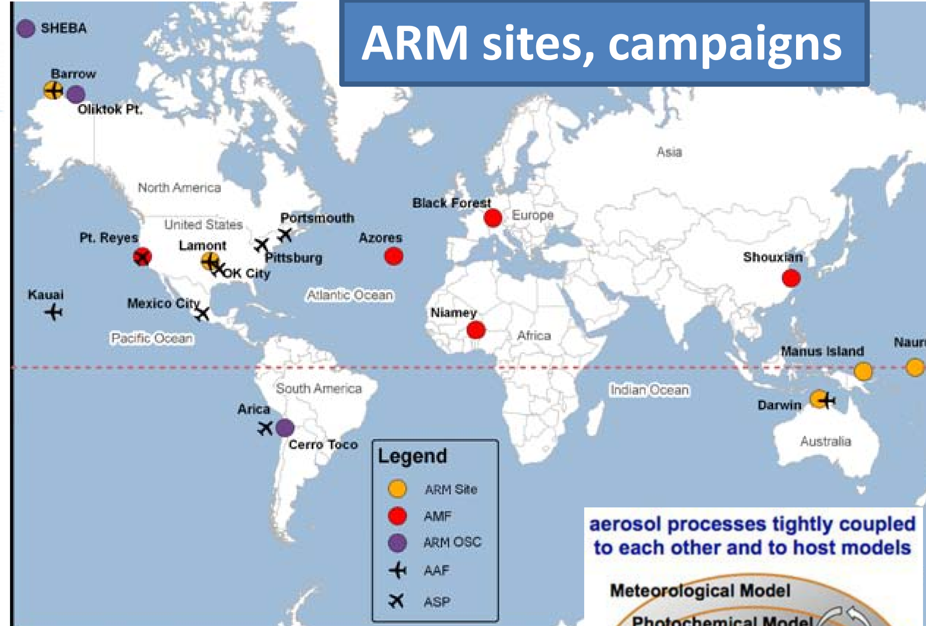
Obs color
Models
black/gray

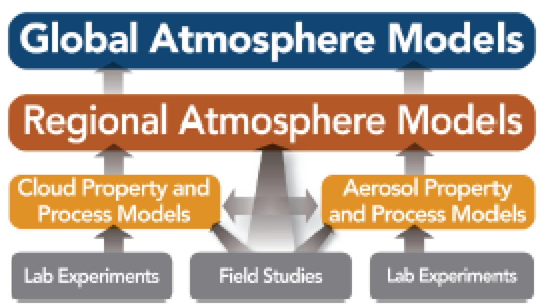
ARM provides long-term measure of cloud and aerosol properties (http://www.arm.gov/instruments)

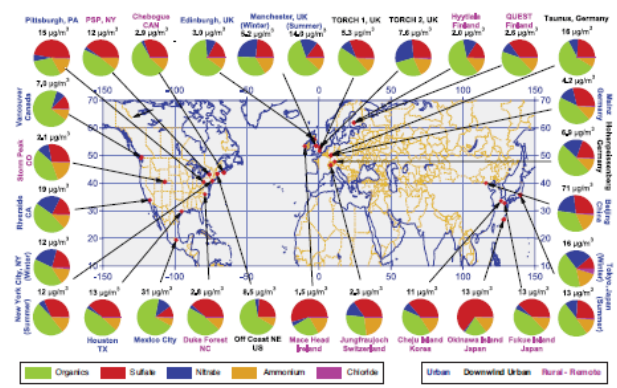
Aerosol observing system: aerosol absorption, concentration, scattering, backscattered radiation, CCN, hygroscopic growth, inorganic composition, number concentration, size distribution

Cimel sunphotometer, Aerosol profiles (aircraft), Radiometers, Lidar, Spectrometer

ARM sites, campaigns





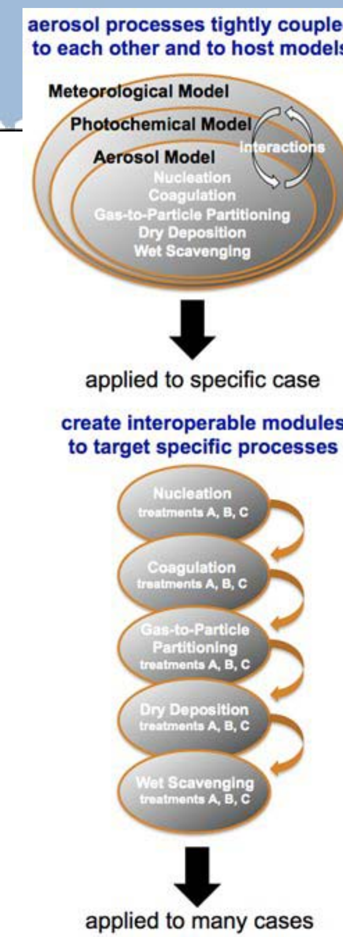


Aerosol composition measured at the surface at various locations around the world (Zhang et al. 2007).

Organic aerosol research

PNNL:
Mirage modal aerosol microphysical scheme, in WRF and CAM5 models

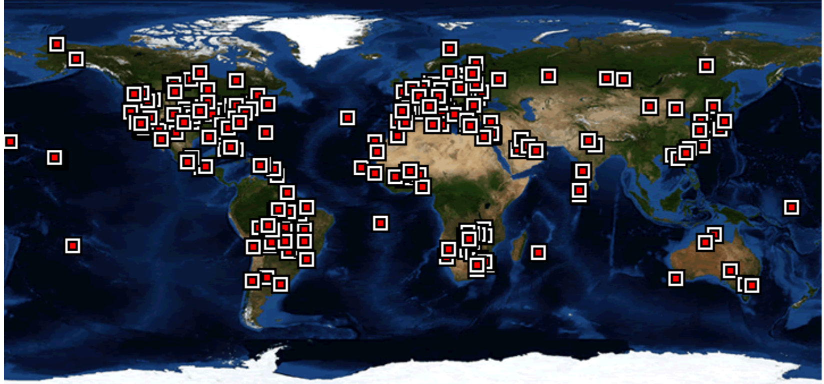
Aerosol microphysical module testbed

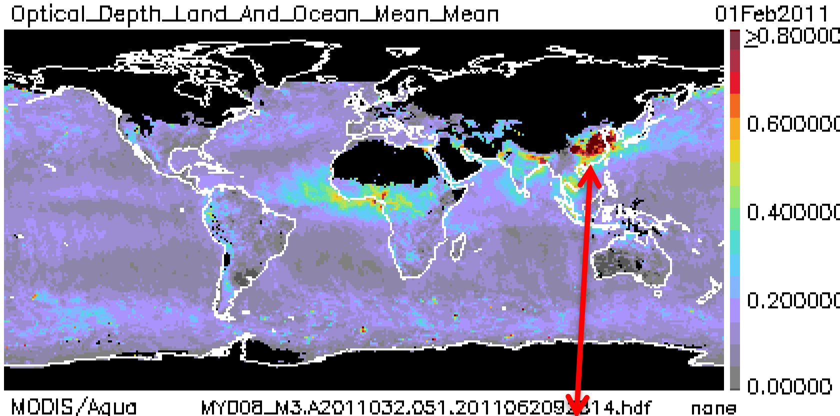


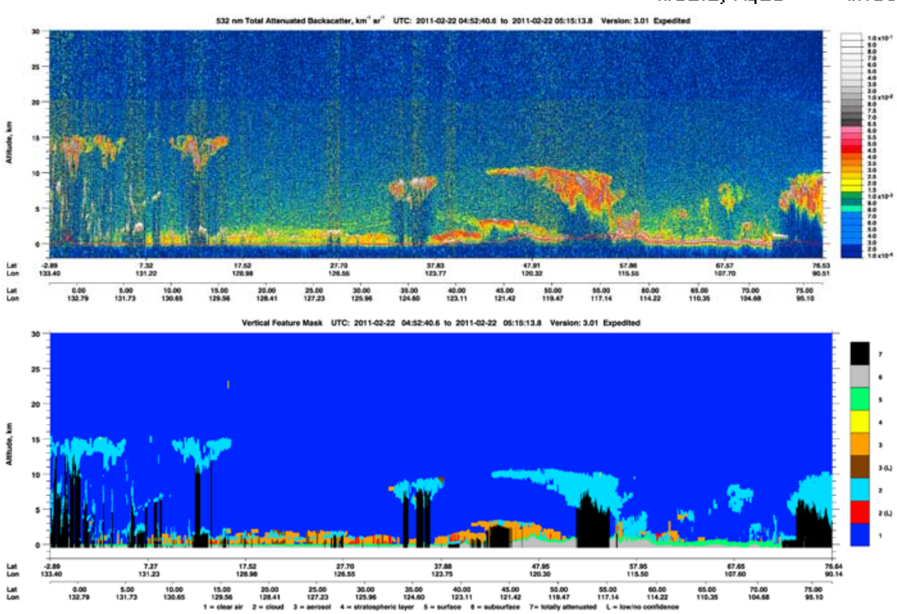
- AERONET network of sun photometers (15+ years of AOD, Angstrom parameter retrievals)

http://aeronet.gsfc.nasa.gov/new_web/aerosols.html

- MODIS, MISR (AOD)
- Calipso (infrared radiometer - vertical distribution)
- Field campaigns
- Models: GEOS-5, GISS







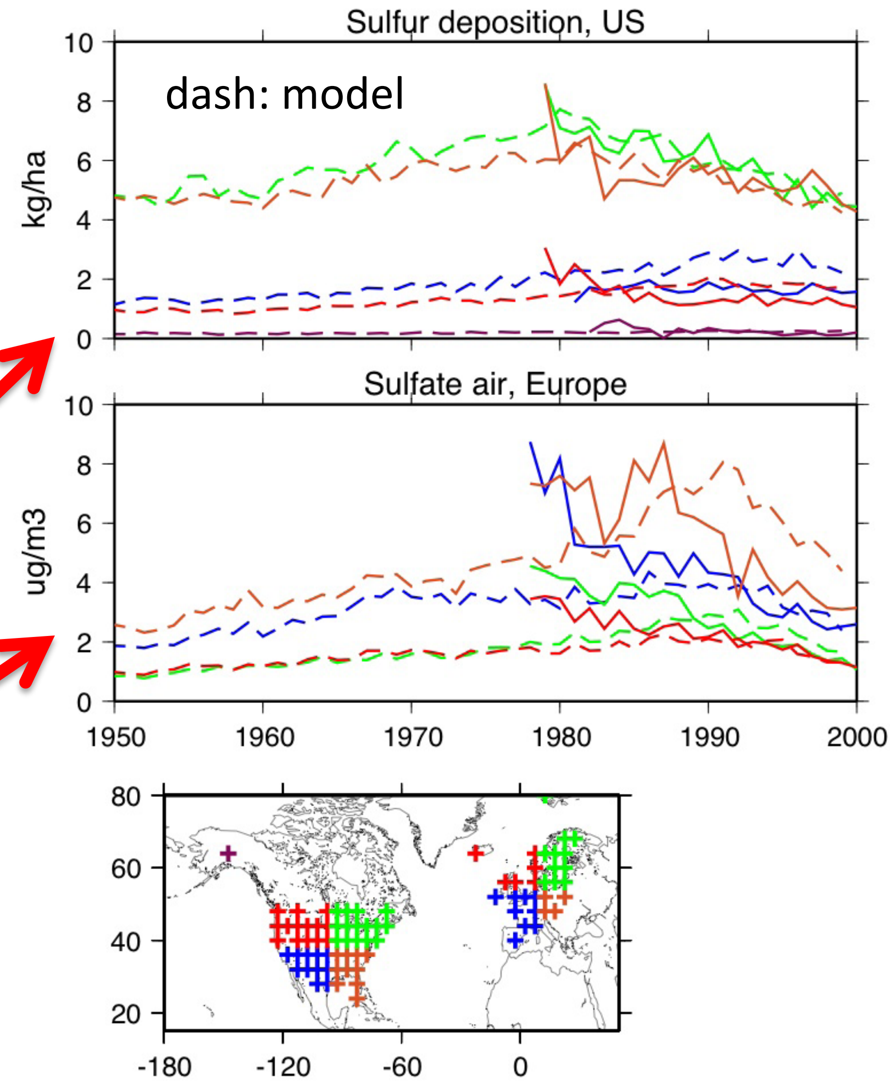
Concentration, Deposition Monitoring Networks

IMPROVE: US air concentrations for sulfate, nitrate, dust, organic, elemental carbon

NADP: sulfur and nitrate deposition since 1980

EMEP: European air concentrations, deposition for sulfate, nitrate since 1980

EANET: Asian acid deposition, since 1998



Koch et al., J Clim, in press

Aerosol uncertainties: about 1 Wm^{-2}

1. Aerosol sources, histories
   - What is natural: how have dust, burning, bio-sources changes?
2. Aerosol size, mixing state, shape; Observed, modeled
3. Closure (remote vs in-situ)
4. Organic aerosol load, optical properties, hygroscopicity

5. a. Warm cloud: validation of aerosol microphysical models
   b. Ice clouds: role of soot-cloud effects in situ
   c. Thermal atmospheric changes: coordinated field-model study

6. BC mitigation potentials (how warming is BC + co-emitted species?)

7. Detangling aerosol historical impacts on climate