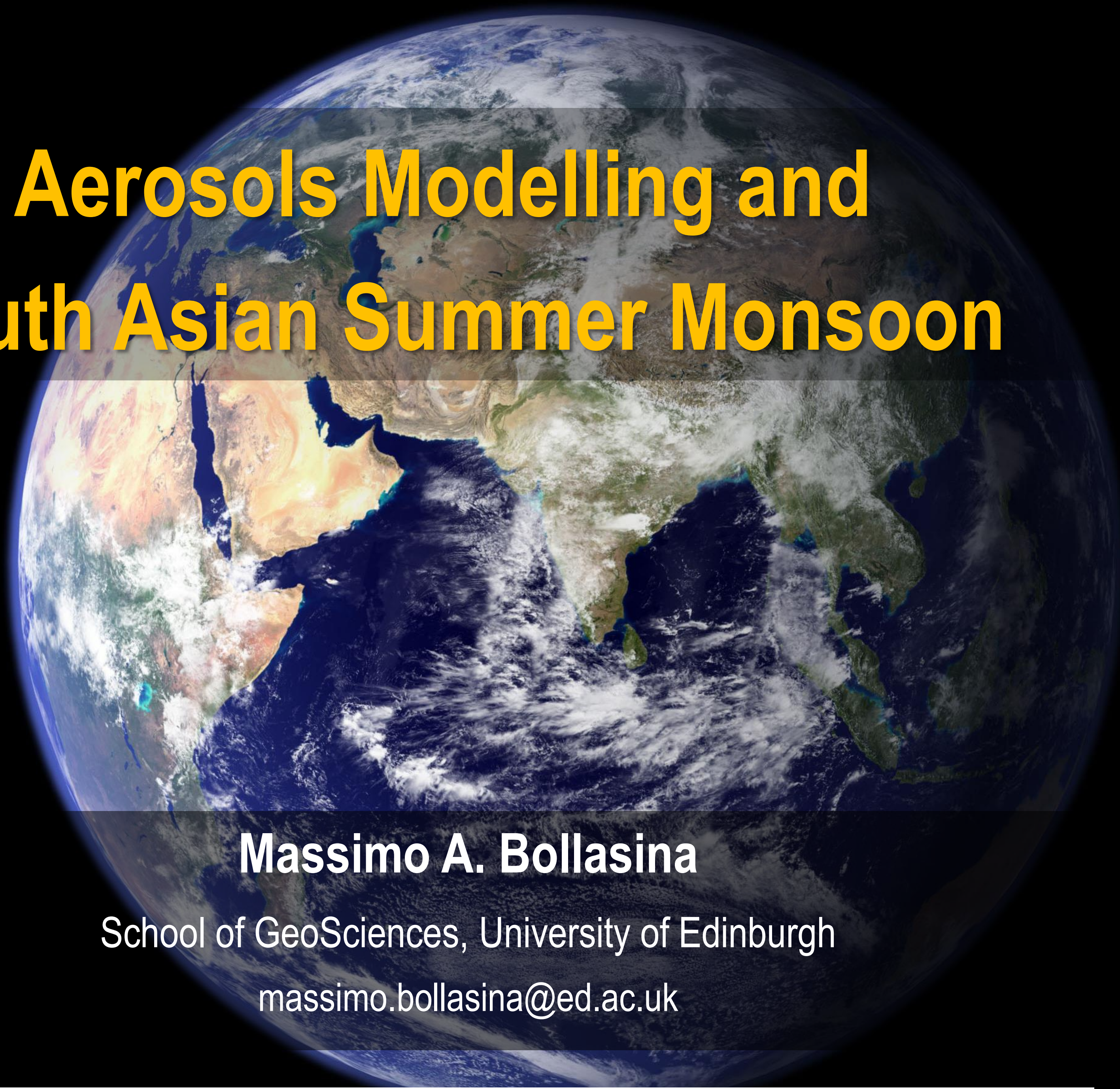


Aerosols Modelling and South Asian Summer Monsoon

Massimo A. Bollasina

School of GeoSciences, University of Edinburgh

massimo.bollasina@ed.ac.uk

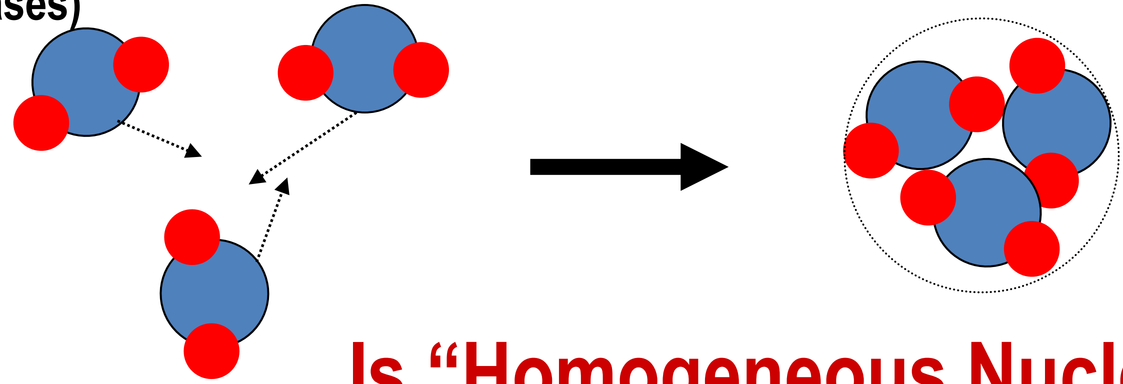
Why are the sunset red?

For small particles, Rayleigh scattering: $1/\lambda^4$

How do clouds form?

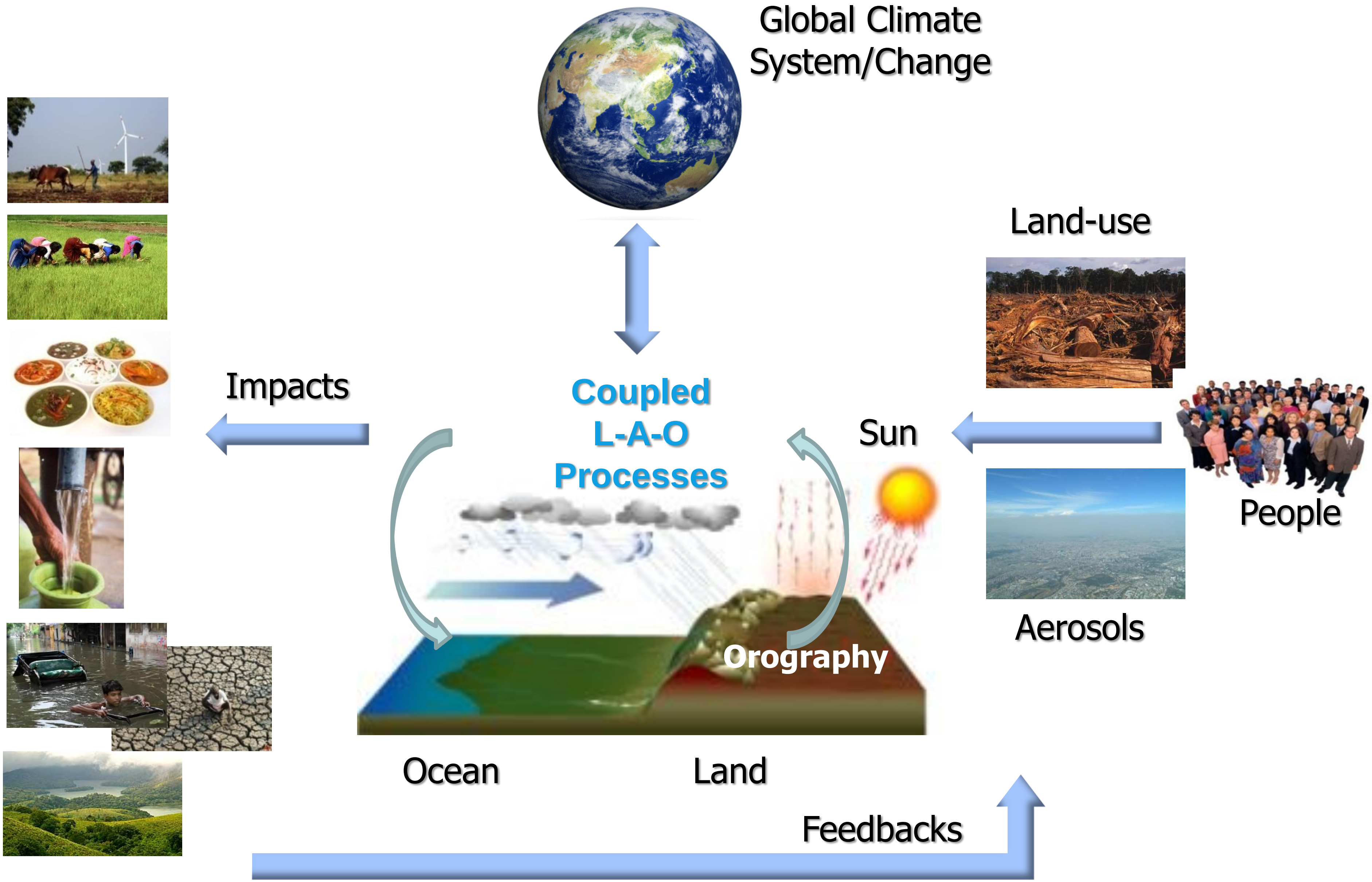
Chance collisions of H_2O molecules (more likely as vapour pressure increases)

Embryonic water droplet large enough to remain intact



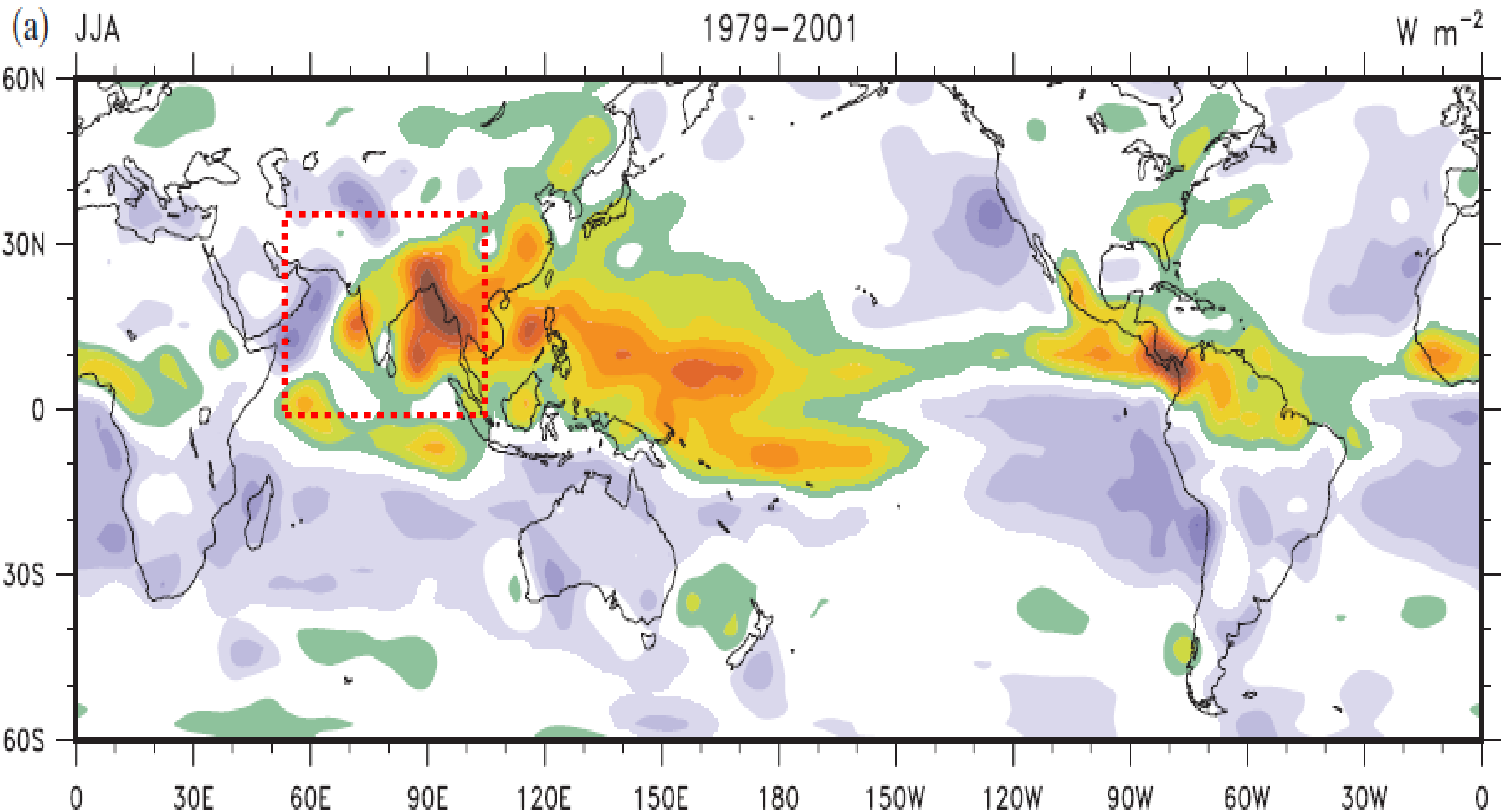
Is "Homogeneous Nucleation" enough?

The ASM: a fully coupled system



Changes in the ASM have important impacts/implications

Vertically-integrated diabatic heating (Trenberth and Stepaniak 2004)



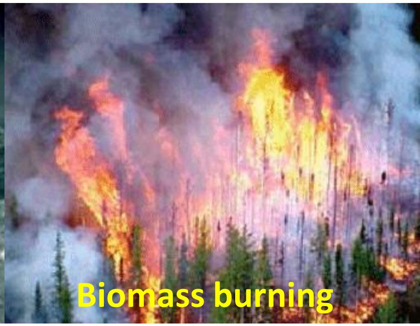
Setting the stage …

- Hydroclimate: mainly precipitation, but not only
- Precipitation: large heterogeneity, result from many physical processes, vital importance
- Controversial results: many uncertainties, observations vs. models (this is not a complete assessment)

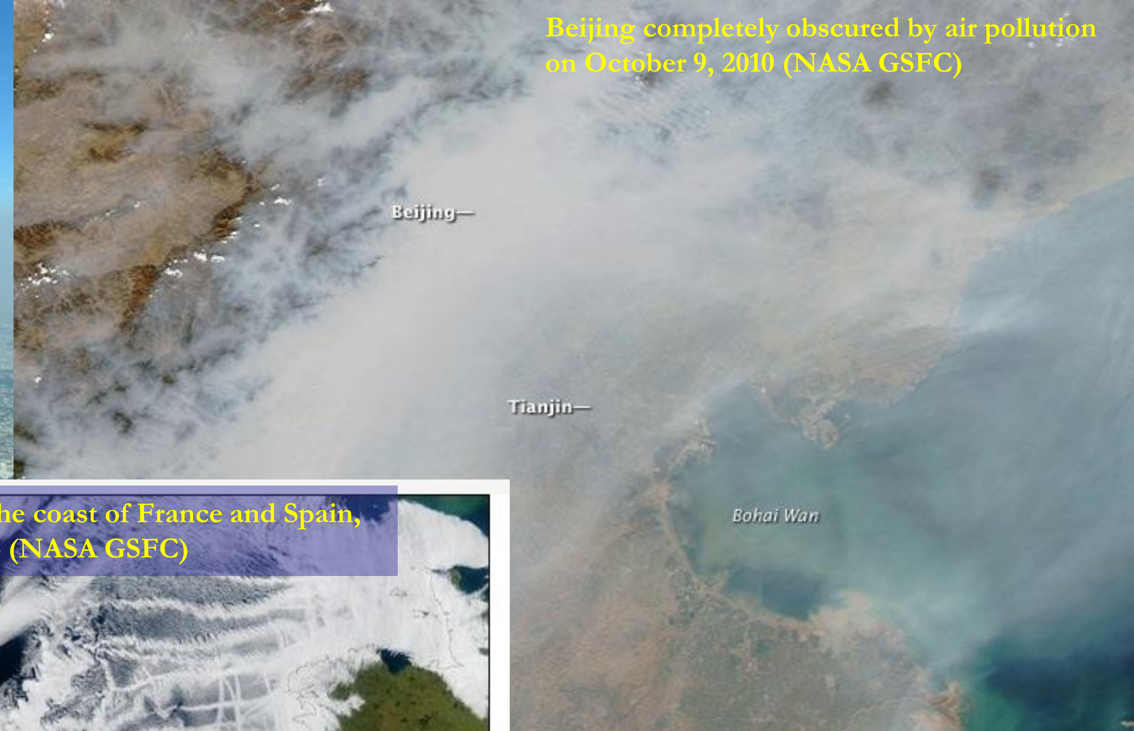
Aerosols: changes in atmospheric/surface heating gradients, diabatic heating from rainfall, circulation

A world of aerosols

- Aerosol: a suspension of fine (10^{-2} - 10 µm) liquid or solid particles in the air
- About 10% of global atmospheric aerosol mass is generated by human activities, concentrated near or downwind of sources
- Anthropogenic aerosols: urban and industrial emissions, domestic fire and combustion, agricultural burning, dust from overgrazing & deforestation
- Natural aerosols: wildfire smoke, sea salt, wind-blown soil dust, volcanic ash
- Primary (directly emitted in the atmosphere) and secondary (formed by chemical reaction from precursors trace gases; SO_2 , NO_x -> sulfates, nitrates)
- Examples: sulfate, soot (black carbon), organic carbon, dust, sea salt

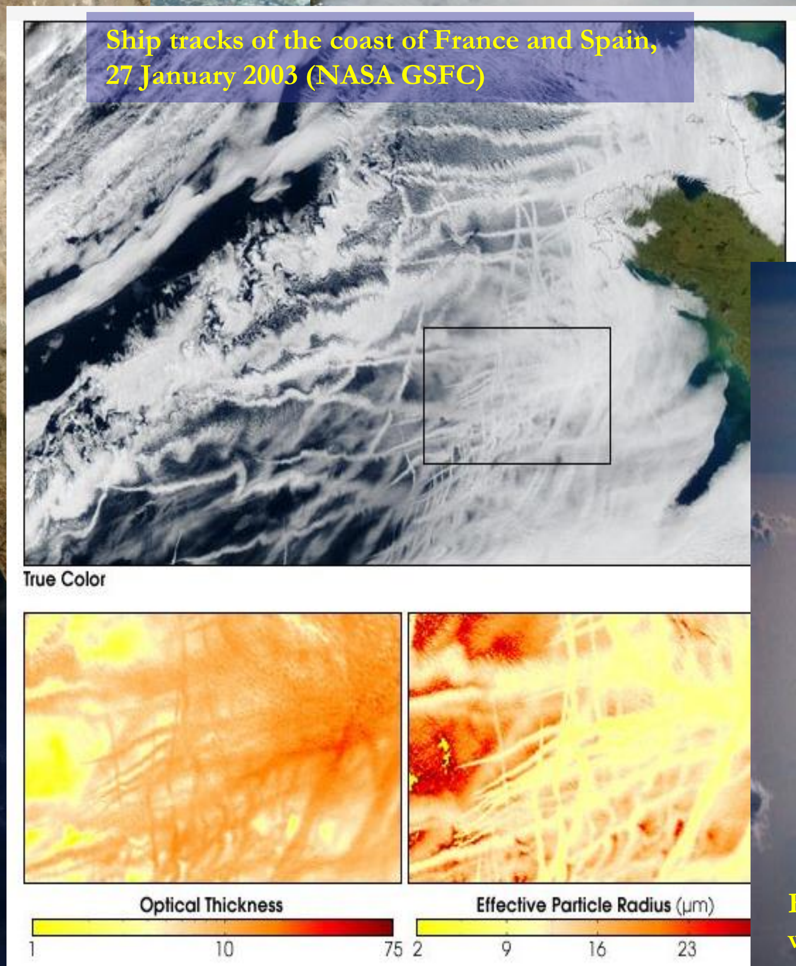


Pollution in Mexico City (NCAR)



Beijing completely obscured by air pollution on October 9, 2010 (NASA GSFC)

California fires 26 October 2003 (NASA GSFC)



Ship tracks of the coast of France and Spain, 27 January 2003 (NASA GSFC)

Biomass burning over Amazon in 2005 dry season with embedded cumulus clouds (NASA GSFC)

Why should be care about aerosols?

Aerosols affect:

- **Visibility**
- **Human health**
- **Air quality**
- **Biogeochemical cycles and ecosystems (as nutrients)**
- **Air traffic (Volcanic eruptions)**
- **Climate (radiation, chemistry, rainfall)**

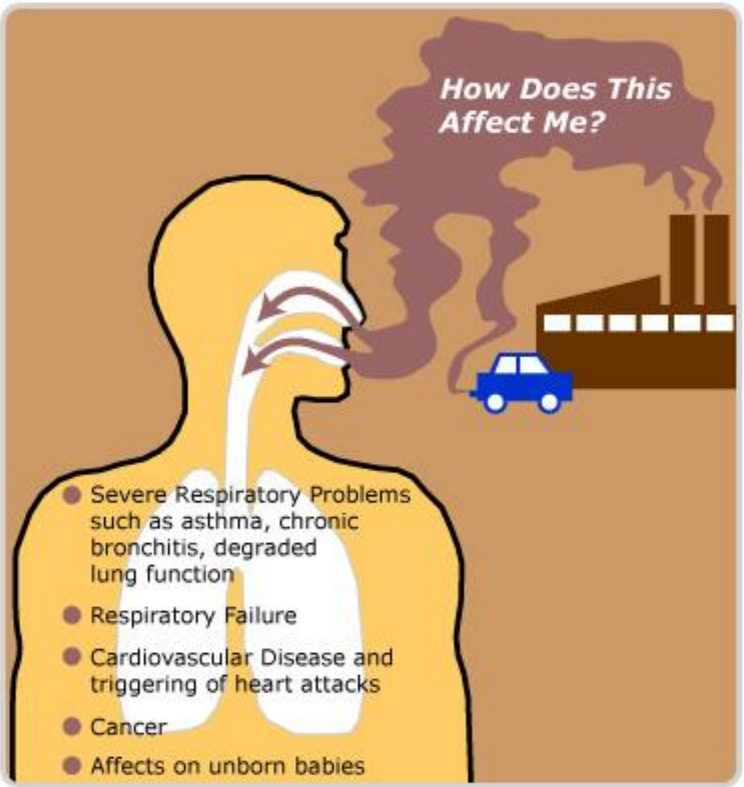
Aerosols are important from molecular to global scale

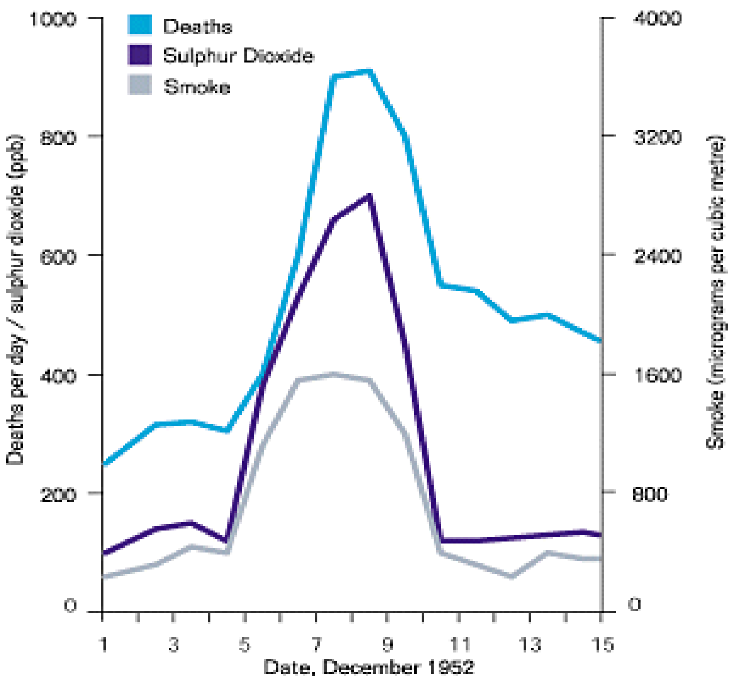
Which aerosol properties should a model be able to simulate in order to be useful in the areas above?

Aerosols and human health

1952: the "London smog disaster"

A period of cold weather, combined with an anticyclone and windless conditions, collected airborne pollutants—mostly arising from the use of coal—to form a thick layer of **smog** over the city

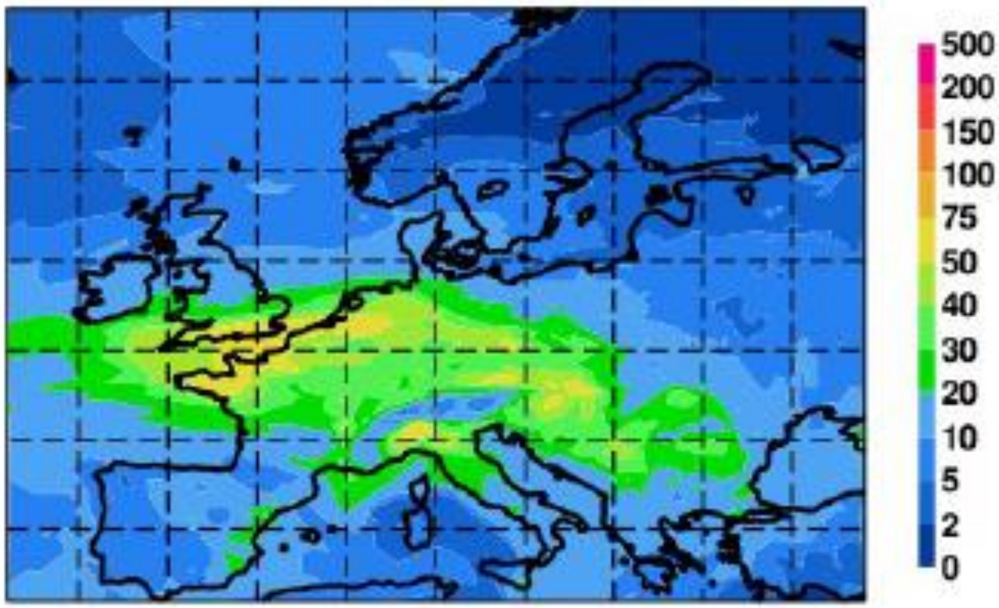




Aerosol properties

- Mass concentration
- Size distribution of the number
- Chemical composition
- Mode of production
- Mixing state
- Solubility and water uptake
- Shape

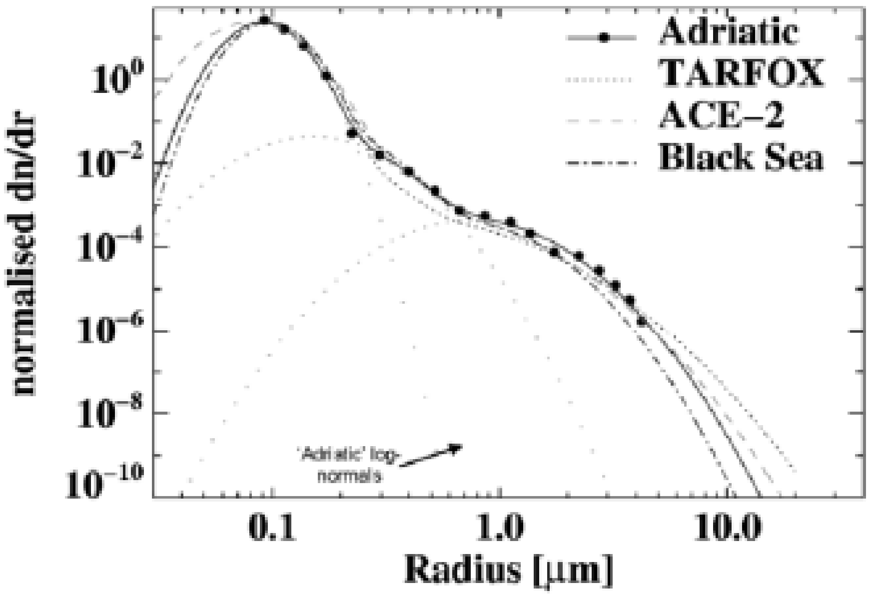
Aerosol mass



Mass concentration of aerosols smaller than 10 µm (PM10) in µg m^{-3}. MACC Air Quality forecast for 24 October 2012.

- Concentrations in µg m^{-3}, typically referred to as Particulate Matter (PM) in the air quality community.
- Aerosol models often use the aerosol mass mixing ratio, in kg[aerosol] kg[dry air]$^{-1}$.

Aerosol size distribution



Average number size distribution from aircraft measurements of pollution aerosols (Osborne et al., 2007)

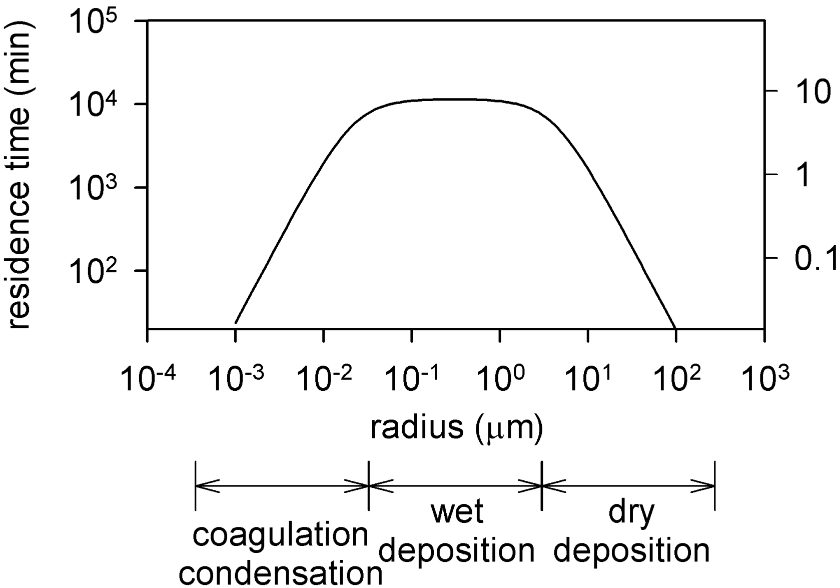
The size distribution is the distribution of particle number (or surface or volume) as a function of particle radius

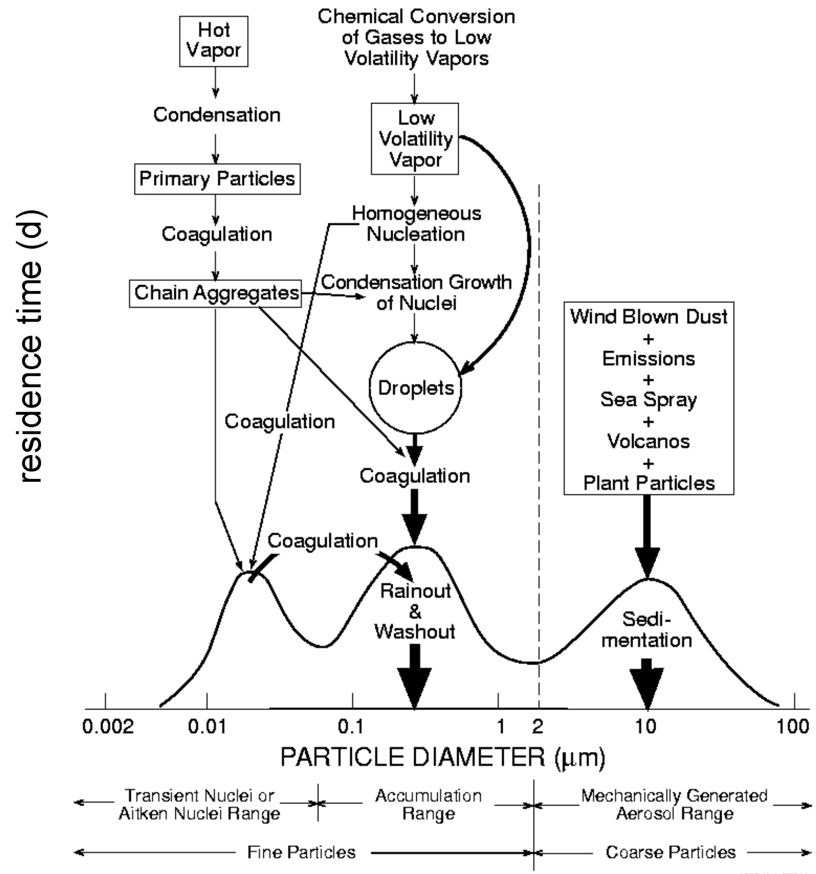
- The size distribution typically exhibits local maximums, called **modes**.
- Q: Why are there maximums and minimums?

Aerosol modes

Name(s) of mode	Nucleation, Aitken, Fine	Accumulation, Fine	Coarse
Typical range for aerosol radius r (μm)	$r < 0.05$	$0.05 < r < 0.5$	$0.5 < r$
Typical production process	Conversion from gas to aerosol	Coagulation of smaller aerosols, condensation of gases onto existing aerosols, combustion	Friction

Aerosols come from a variety of sources, and reside in the atmosphere for weeks





Seinfeld and Pandis

“fine” **diameters D < 2.5 microns**

sulfate, ammonium, organic carbon, elemental carbon

Nuclei mode 0.005 to 0.01 microns

condensation of vapors

Accumulation mode

0.1 to 2.5 microns coagulation

“coarse” **diameters D > 2.5 microns**

natural dust (e.g. desert)

mechanical processes

crustal materials

biogenic (pollen, plant fragmets)

Aerosol size distribution

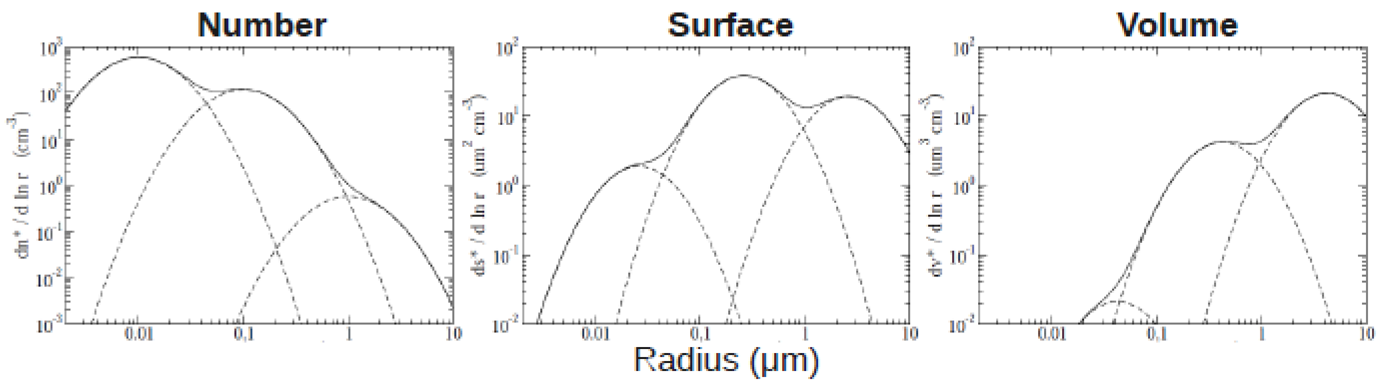
- To describe mathematically the distribution for a given aerosol mode, functions that can cover a large range of sizes are useful.

- The most popular function is the *lognormal distribution*, which describes well the typical distributions observed in the atmosphere:

$$\frac{dN}{d\ln r} = N_0 \frac{1}{\sqrt{2\pi}\,\sigma_0} \exp\left(-\frac{1}{2}\left(\frac{\ln(r/r_0)}{\sigma_0}\right)^2\right)$$

N: Aerosol number
r: Aerosol radius
N_0: Total aerosol number
r_0: Mean/median radius
σ_0: Standard deviation

Aerosol size distribution



Three lognormal distributions with r_0 = 0.01, 0.1, and 1 µm, σ_0 = 0.7. From Boucher (2012)

- Aitken-mode aerosols dominate the distribution of the number.
- Accumulation-mode aerosols dominate the distribution of the surface.
- Coarse-mode aerosols dominate the distribution of the volume.

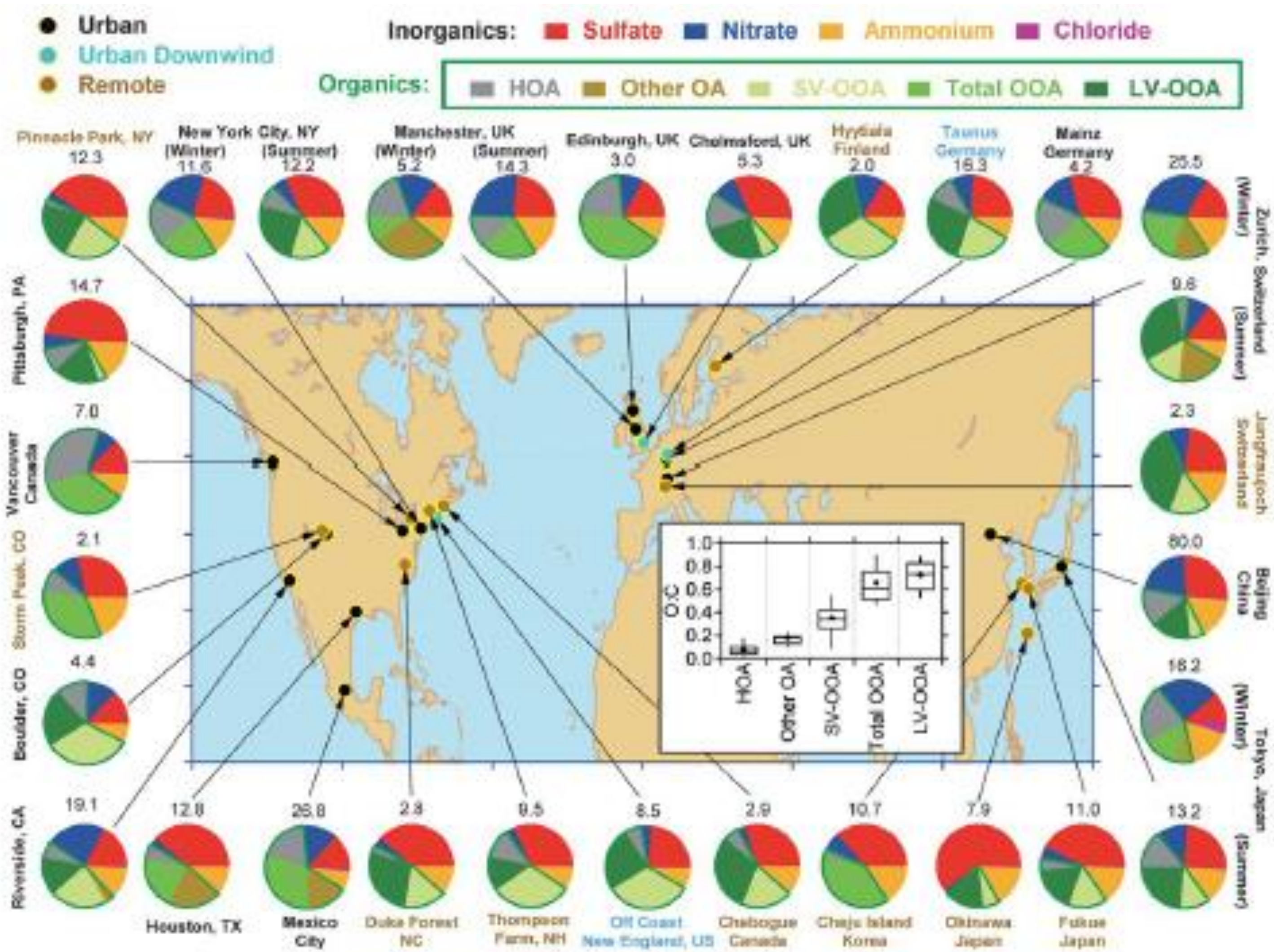
Main aerosol species

- Sulphate (ion SO_4=), found as sulphuric acid H_2SO_4, and ammonium sulphate $(NH_4)_2SO_4$
- Nitrate (ion NO_3–), found as nitric acid HNO_3, ammonium nitrate NH_4NO_3
- Mineral dust
- Oxides (silica, iron oxides), calcium carbonate, ...
- Sea-salt (NaCl)
- Carbonaceous
- Black carbon (soot), organic matter

Primary aerosols: Directly emitted into the atmosphere as a particle.
Secondary aerosols: Product of the oxidation of a gaseous precursor.

- Q: What are examples of primary and secondary aerosols?
- Distinguishing between aerosols generated by natural processes and human activities (*anthropogenic*) is also useful, most notably in climate studies.

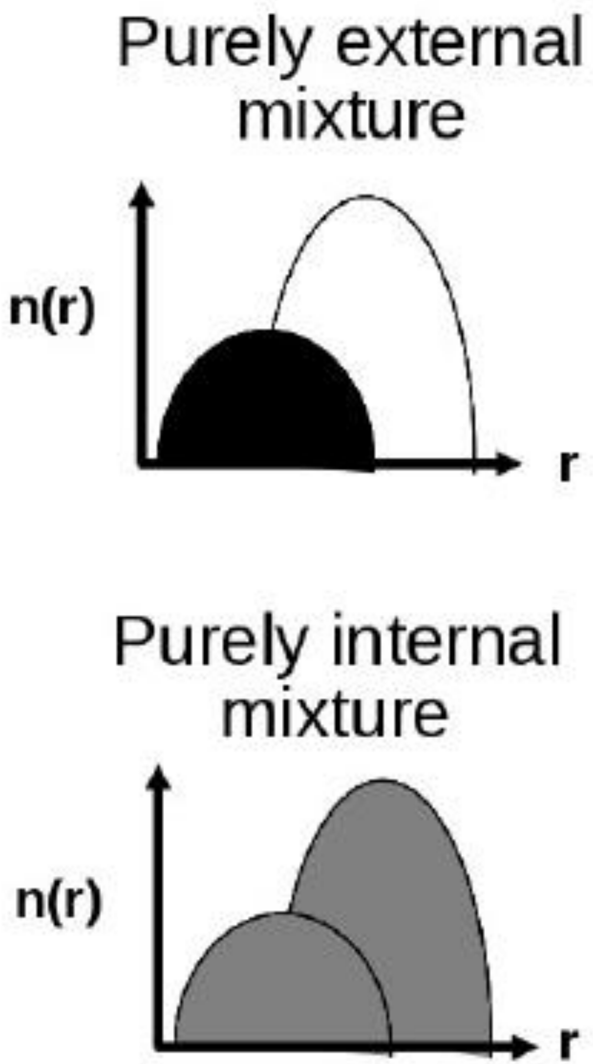
Aerosol chemical composition



Climatology of aerosol mass spectrometer measurements by Jimenez et al. (2009). Only includes organic and non-refractory inorganic species.

Aerosol composition exhibits strong spatial variations, and may also vary strongly in time.

Aerosol mixing state

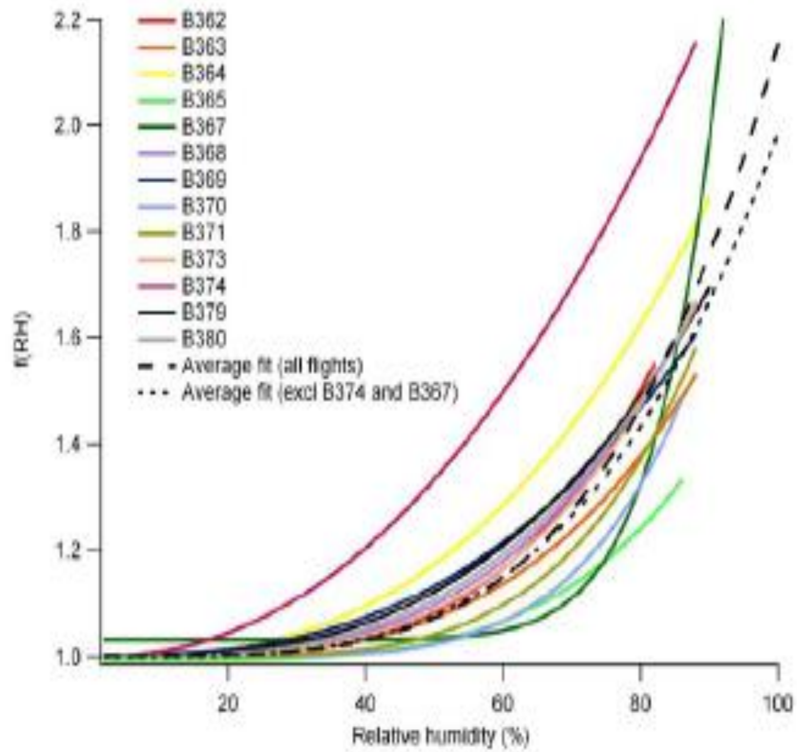


- Composition is governed by chemistry, thermodynamics, and kinetics, driven by temperature, moisture, pH, ...
- *External mixture*: Mixture of particles with distinct chemical compositions.
- *Internal mixture*: Multiple materials in the same particle.
- The internal mixture of a primary aerosol coated by secondary material is common in the atmosphere.

Aerosol solubility and water uptake

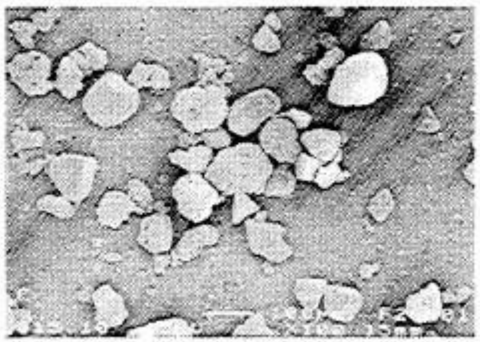
- Aerosols such as sulphate are dissolved into small water droplets. Non-dissolved aerosols can be coated in soluble materials.

- The amount of water condensed onto the aerosol increases with increasing relative humidity: this is the *hygroscopic growth*.

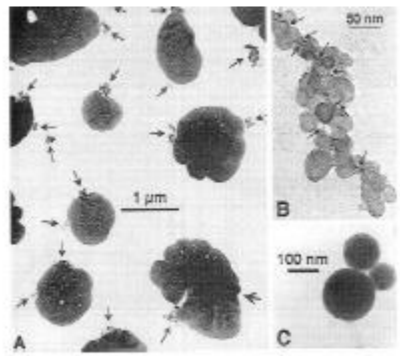


Ratio moist to dry aerosol radius as a function of relative humidity.
From aircraft measurements during the EUCAARI-LONGREX campaign over Europe.
Highwood et al. (2012)

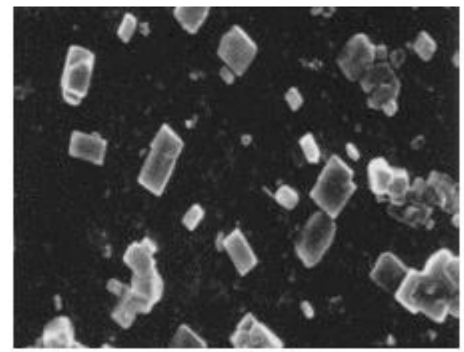
Aerosol shape



Mineral dust (Volten et al., 2005)



Sulphate, soot, and fly-ash (Posfai et al., 1999)



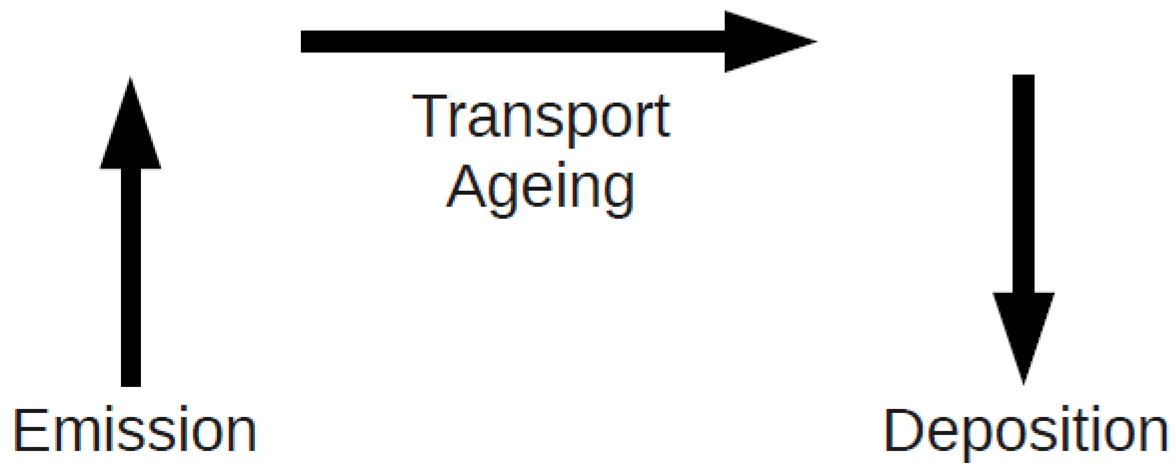
Sea-salt (dry) (Chamaillard et al., 2006)

- Dissolved aerosols are typically spherical.
- Mineral dust exhibits more diverse and complex shapes.
- Shape affects:
  - Aerosol-radiation interactions
  - Chemical reactions on the aerosol surface
  - The ability to serve as ice cloud nuclei

Modellers often make the simplifying assumption that aerosols are spherical.

Aerosol modelling

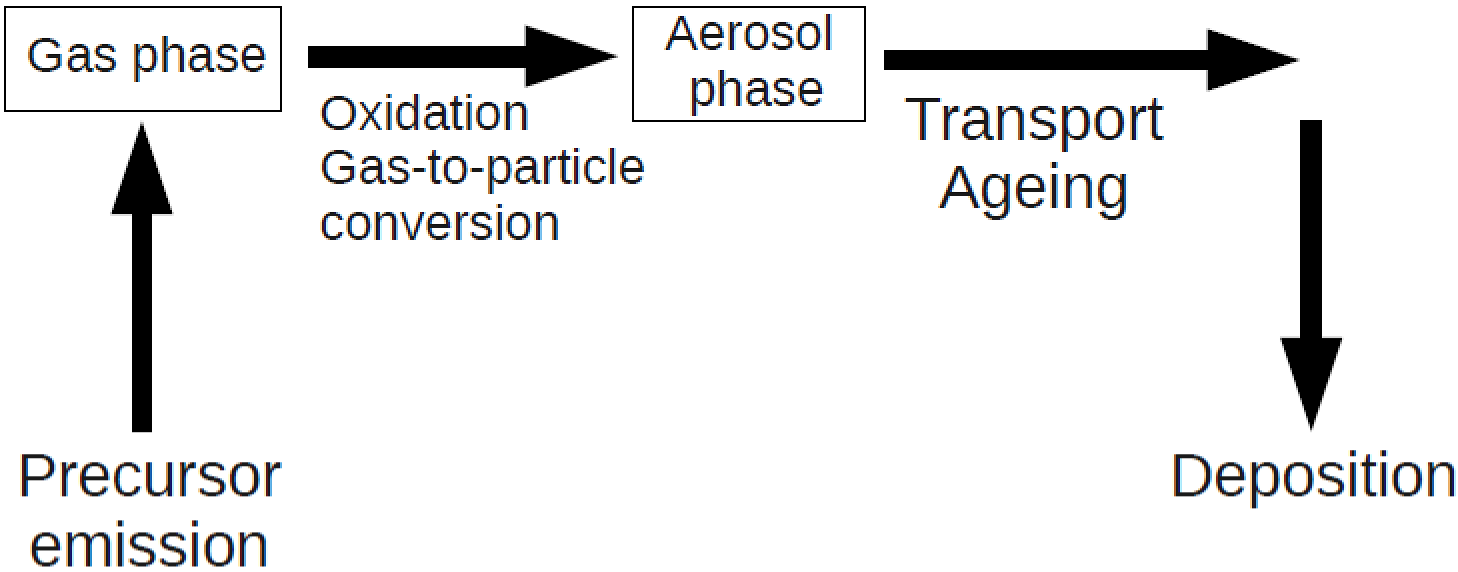
Summary diagram for primary aerosols



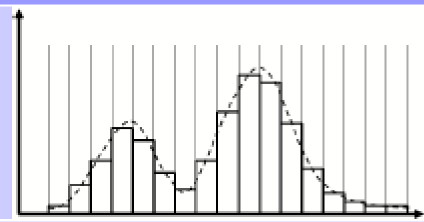
Aerosol aging refers to the change in the composition, size, and mixing state (the extent to which an individual particle contains a complete mixture of all different chemical components of the aerosol population) of the aerosol.

Aerosol modelling

Summary diagram for secondary aerosols



Type of aerosol models

Bulk mass	Sectional	Modal
Simulate modal mass for an external mixture of species.		Simulate modal mass and number for an internal mixture of selected species.
Size distribution is prescribed globally.	Decompose the size distribution in bins.	The mean radius of the size distribution depends on mass and number.
Mass and number are co-varying.	Does not usually represent the mixing state.	Width of the size distribution is generally fixed.

Mathematically, the time evolution of the mass (or number) concentration of a given tracer is given by:

$$\frac{\partial c}{\partial t} + \mathrm{div}\ (c\,\vec{V}) = \mathrm{div}\ (K_m \overrightarrow{\nabla} c) + S - P$$

Aerosol emissions

Emissions of anthropogenic aerosols rely on inventories, which are gridded datasets giving emission rates (kg[species] m^{-2} s^{-1}) for various gases and aerosols

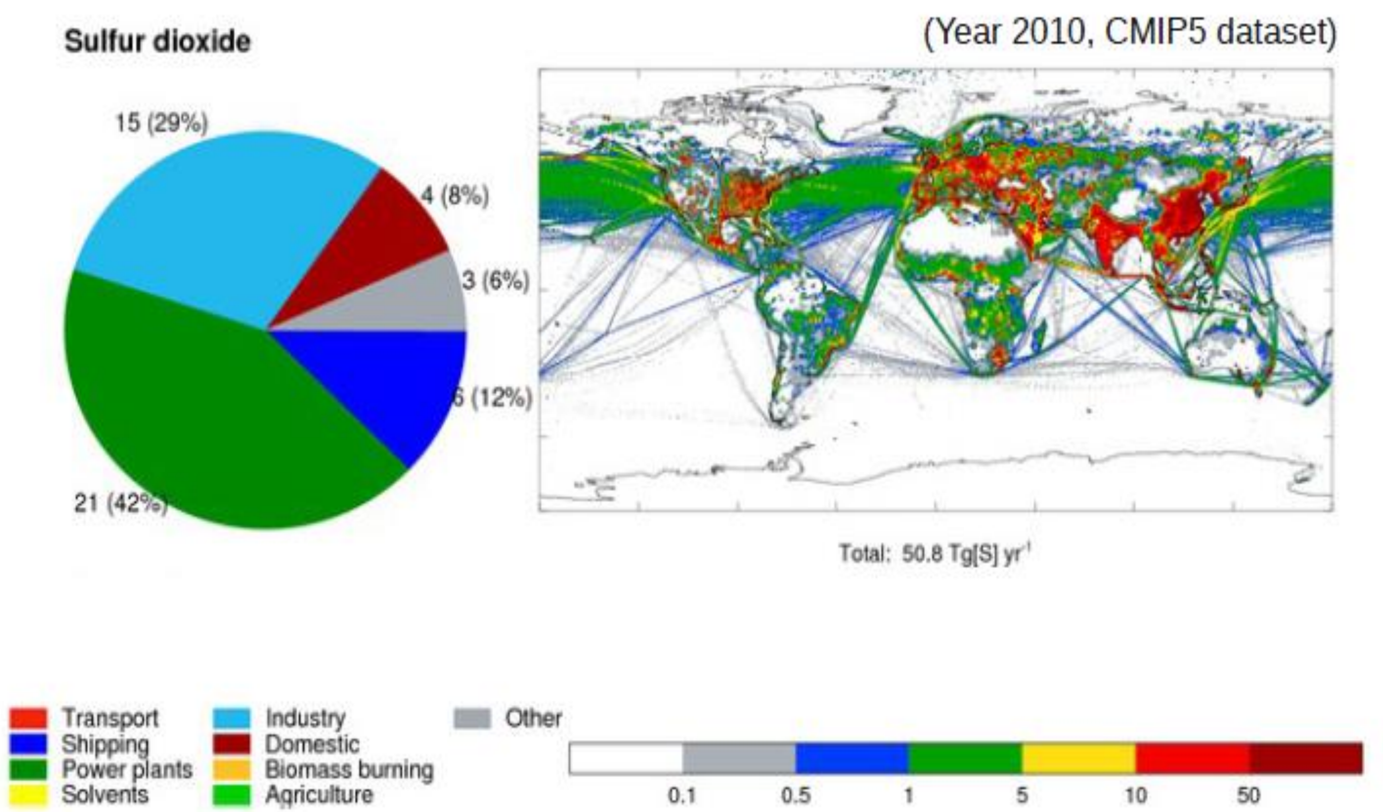
- Global or regional,
- Monthly, seasonal, annual, or decadal basis.
- Emissions of natural aerosols are computed using a parameterisation, when available, that relies on quantities simulated by the model: e.g. wind speed, soil moisture, temperature

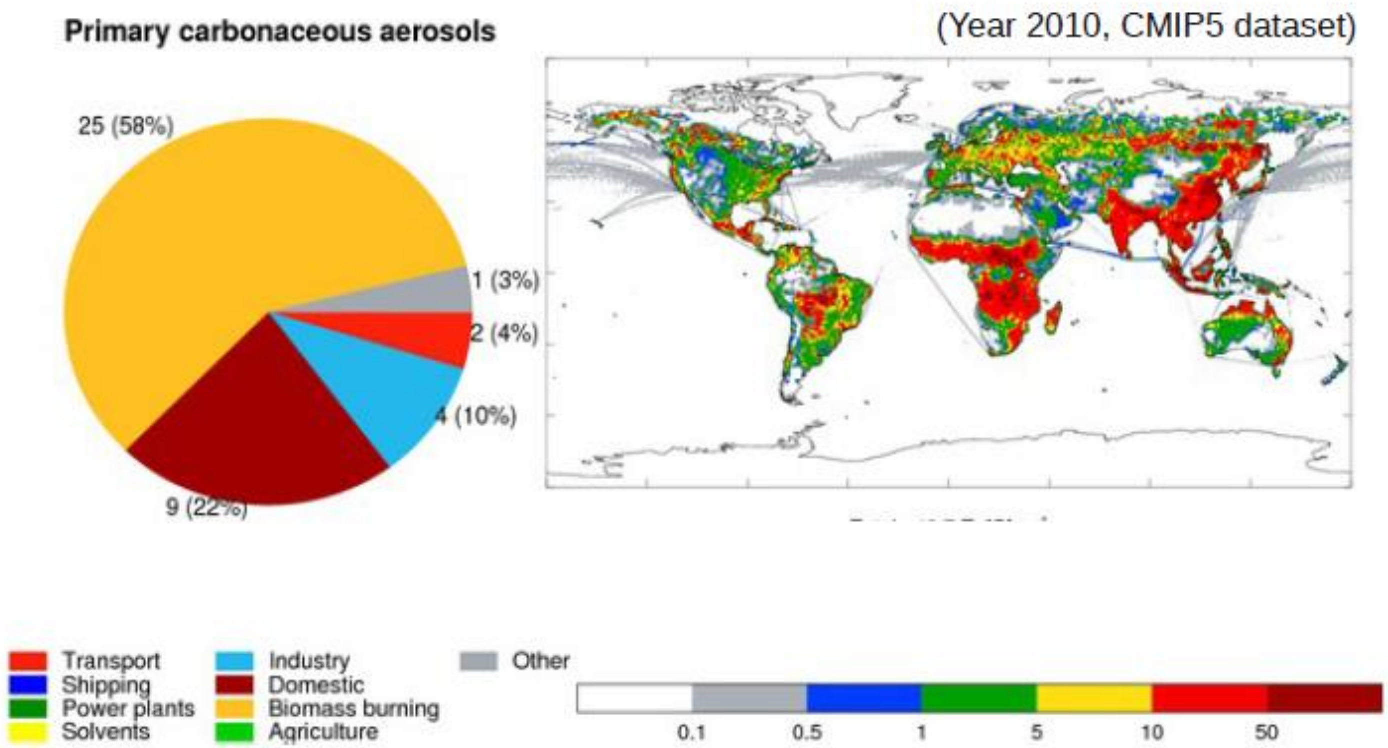
Indicative emission rates for present day, averaged globally and annually

Gaseous precursor	Primary aerosol	Anthropogenic emission rate	Natural emission rate
Sulphur dioxide (SO_2)		50-90 Tg[S] yr^{-1}	10 Tg[S] yr^{-1}
Ammonia (NH_3)		20-50 Tg[N] yr^{-1}	10 Tg[N] yr^{-1}
Volatile organic compounds		5-40 Tg[C] yr^{-1}	80-200 Tg[C] yr^{-1}
	Carbonaceous aerosols from fossil fuels	20-50 Tg[C] yr^{-1}	
	Carbonaceous aerosols from biomass burning	50-90 Tg[C] yr^{-1}	20-40 Tg[C] yr^{-1}
	Mineral dust	40-130 Tg yr^{-1}	1000-3000 Tg yr^{-1}
	Sea-salt		2000-10000 Tg yr^{-1}
Dimethylsulphide (DMS)			10-60 Tg[S] yr^{-1}

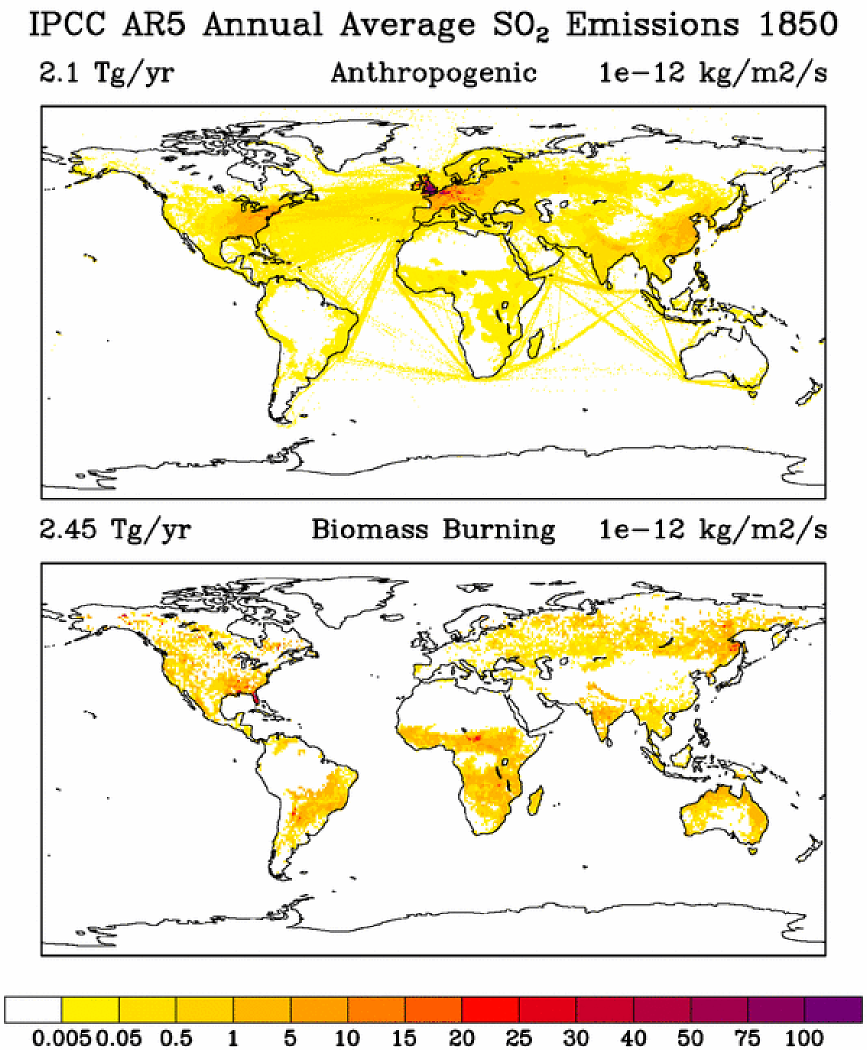
Emission inventories

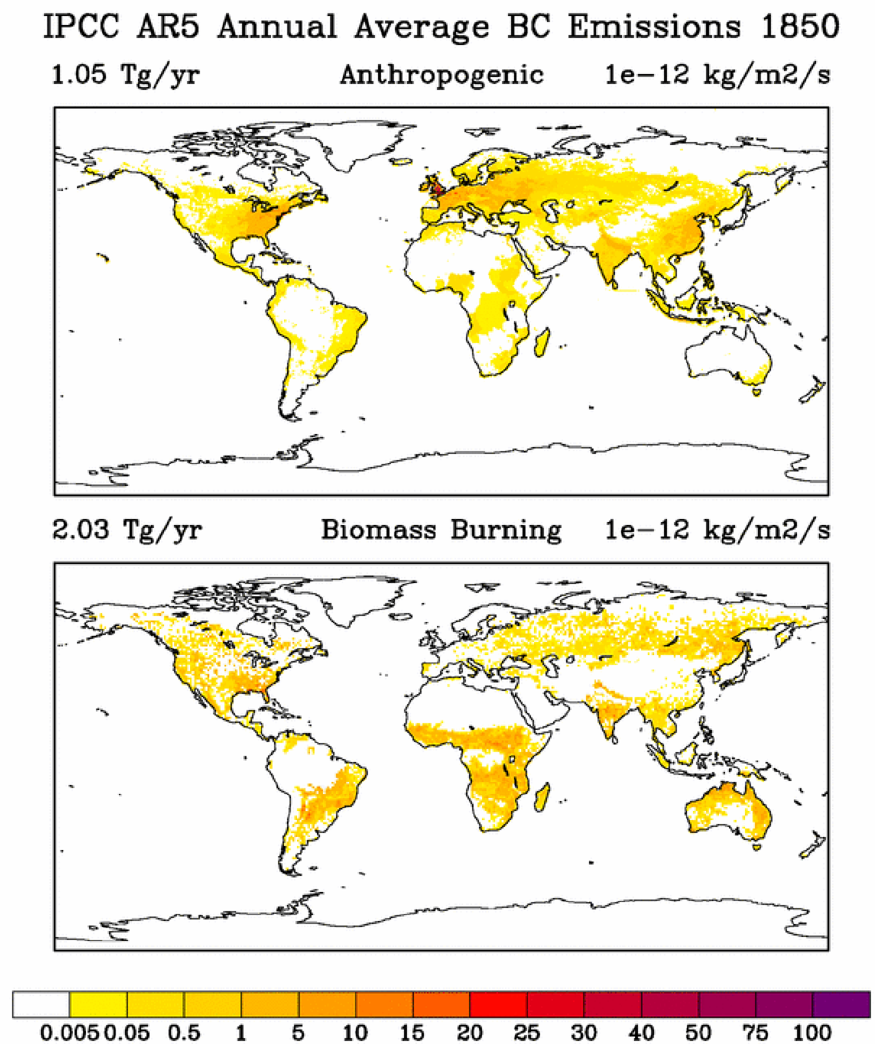
- Anthropogenic emissions are estimated from inventories for various activity sectors:
  - Transport, shipping, aviation
  - Power generation and industry
  - Residential and commercial
  - Agriculture
  - Biomass burning (also includes a natural component)




Primary carbonaceous aerosols
(Year 2010, CMIP5 dataset)
25 (58%)
1 (3%)
2 (4%)
4 (10%)
9 (22%)
Transport
Shipping
Power plants
Solvents
Industry
Domestic
Biomass burning
Agriculture
Other
0.1
0.5
1
5
10
50

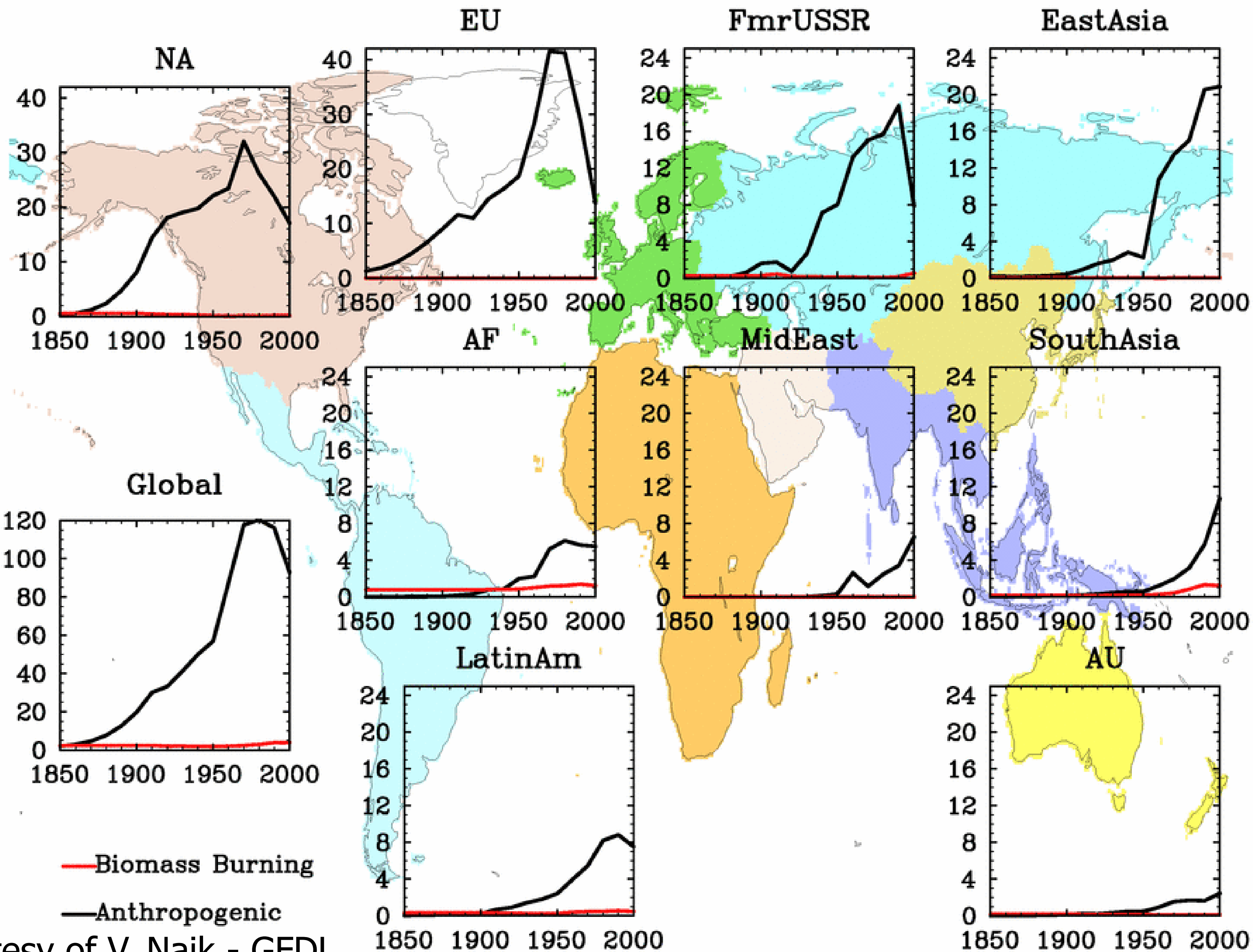
Aerosol emissions: changes since PI time





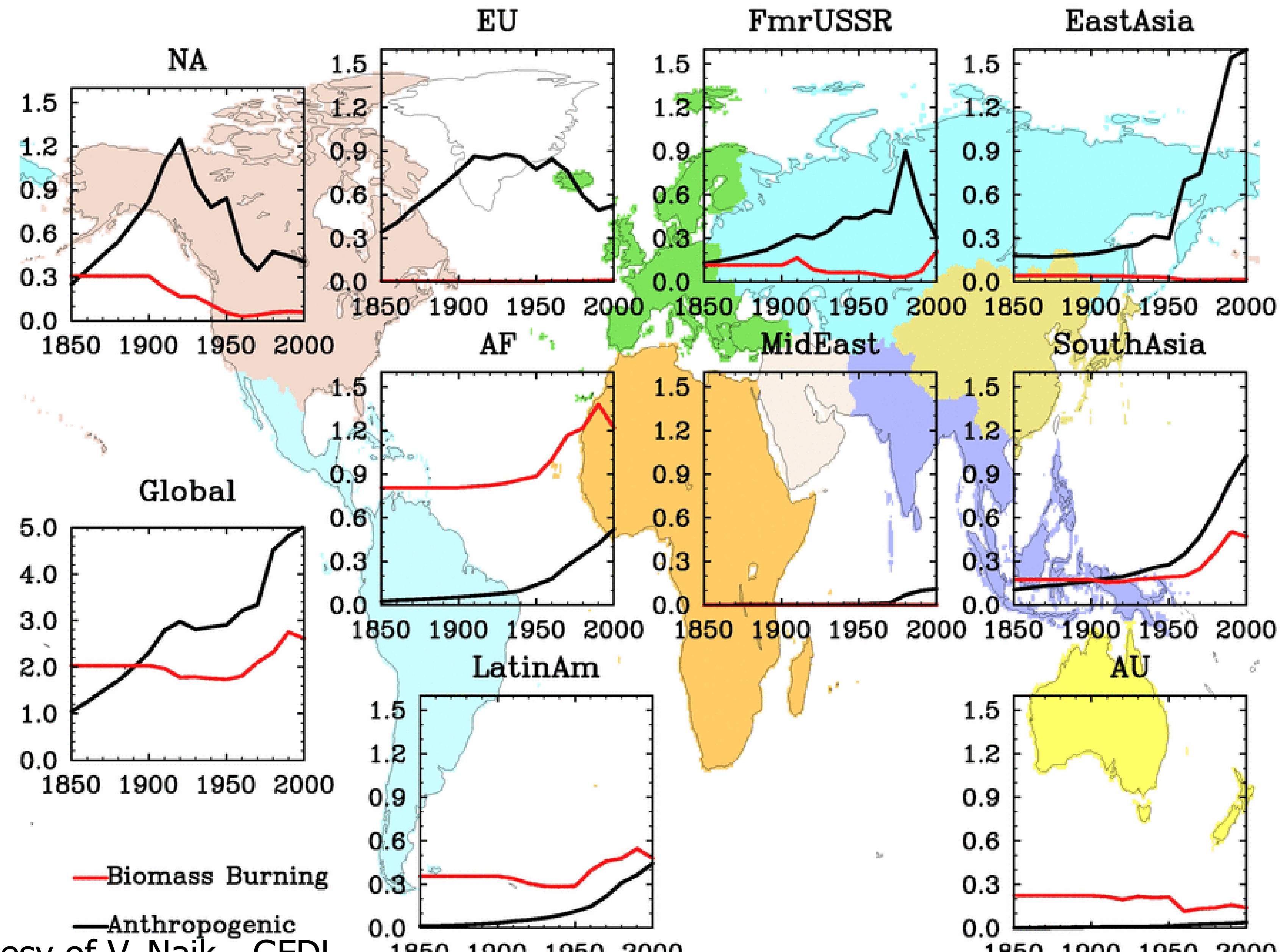
Courtesy of V. Naik - GFDL

Historical Trend - IPCC AR5 SO_2 Emissions (Tg/yr)



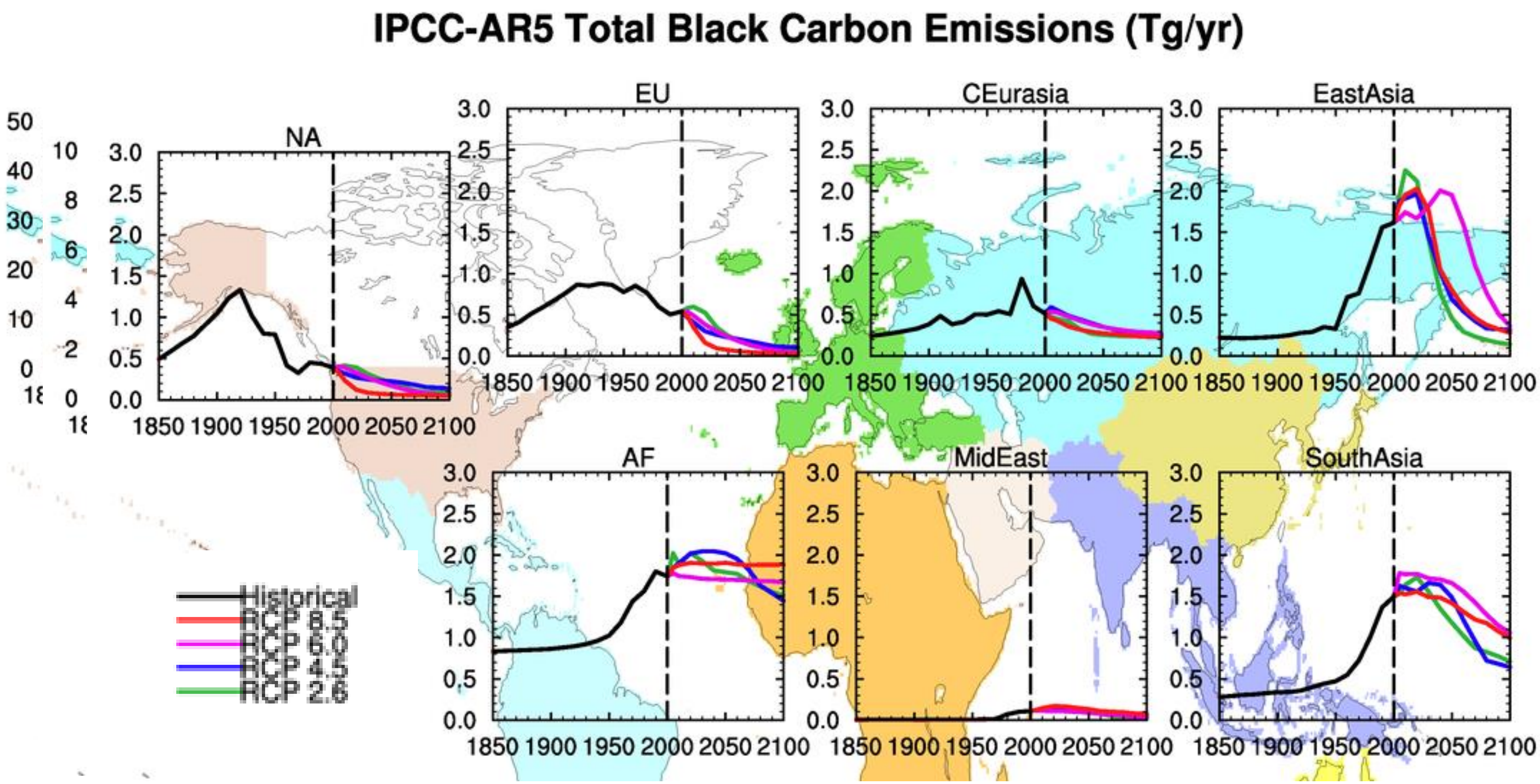
Courtesy of V. Naik - GFDL

Historical Trend - IPCC AR5 BC Emissions (Tg/yr)



Courtesy of V. Naik - GFDL

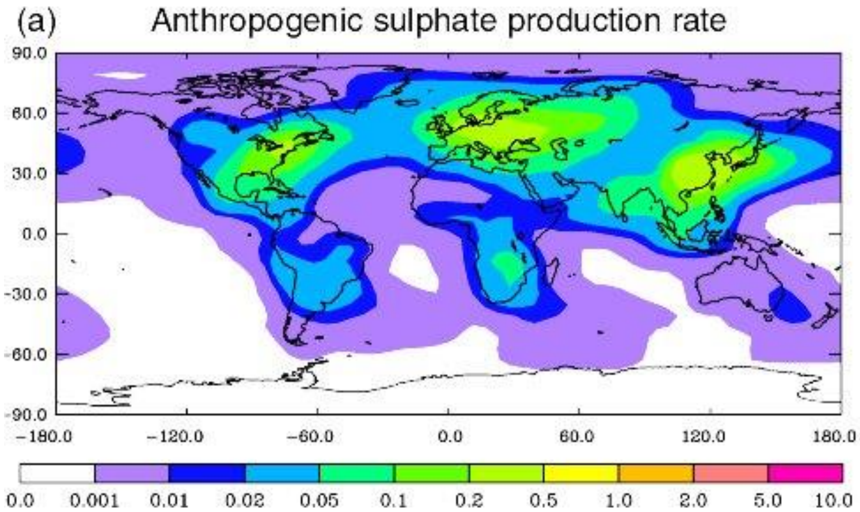
Global aerosol variations: past and future emissions

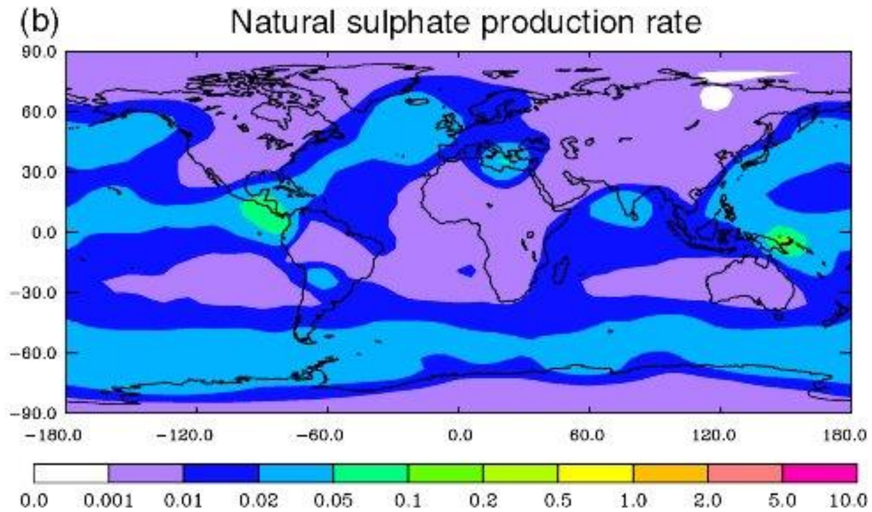


- The <u>true magnitude of the GHG warming is not known</u>, as well as climate forcing/sensitivity
- Aerosols will continue to play a role in <u>regional climate change</u>
- <u>Realistic predictions</u> of future climate change depend on climate models able to accurately represent present climate as well as changes that have occurred over the past century

Distribution: sulphates

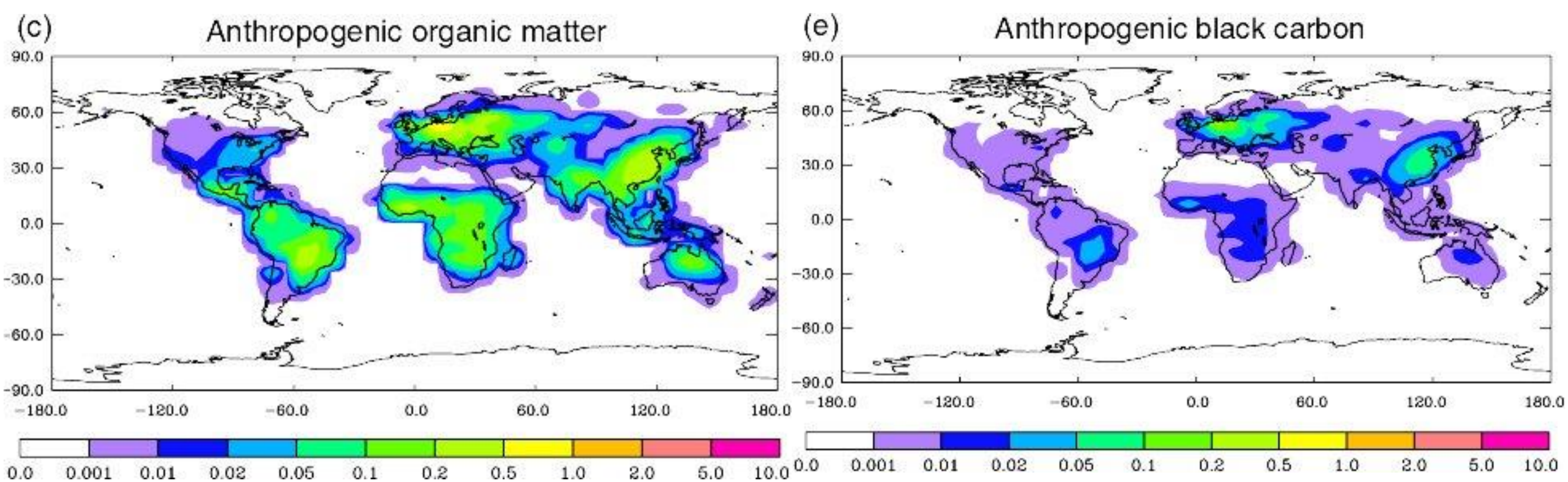
- Formed from gases SO_2 (from fossil fuel or volcanoes) and DMS (from ocean algae)





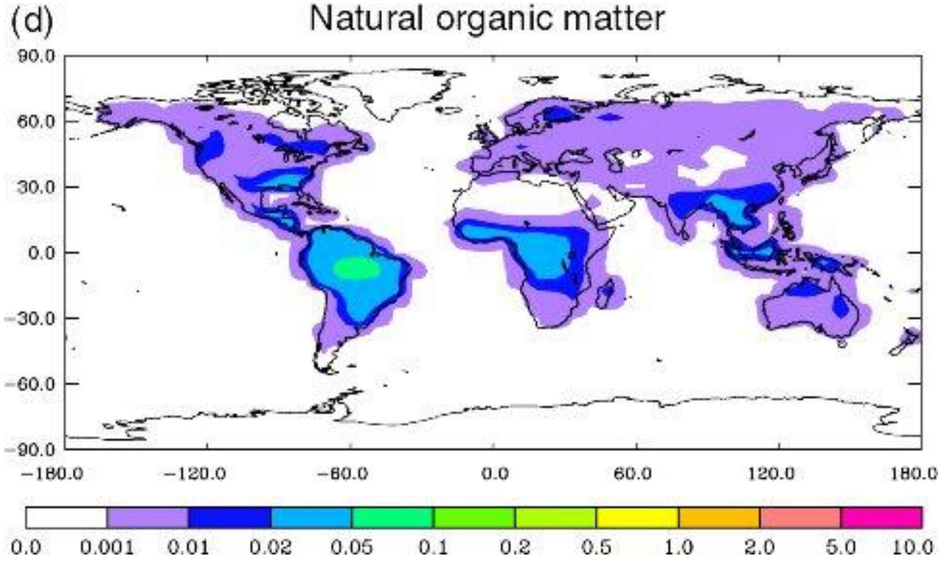
Distribution: carbonaceous from anthropogenic sources

- Fossil fuel burning
- Inventories have an uncertainty of a factor of 2.



Distributions: Biomass burning

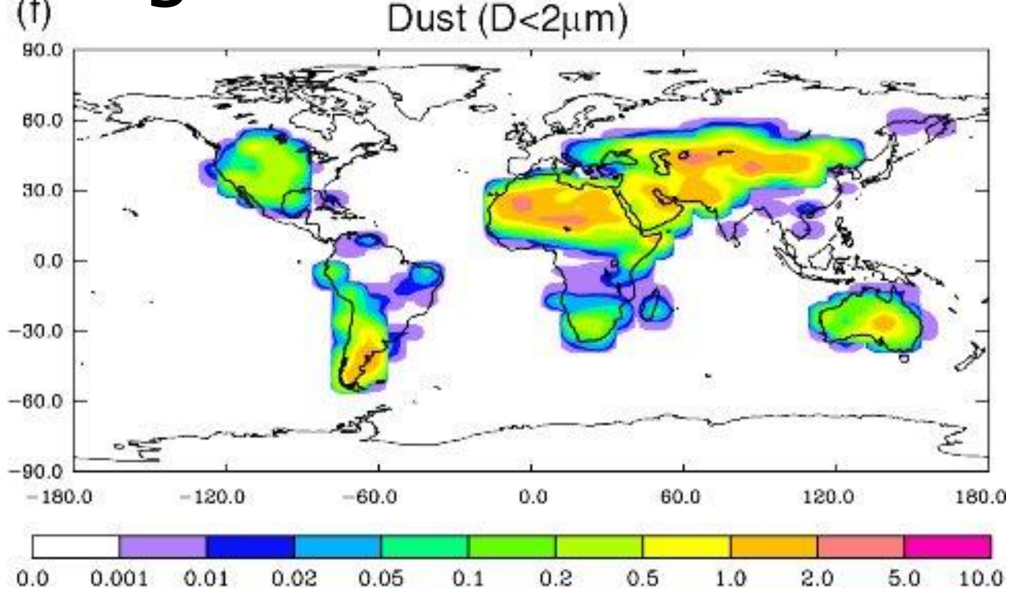
- Some biomass burning is natural.
- Episodic and regional in nature

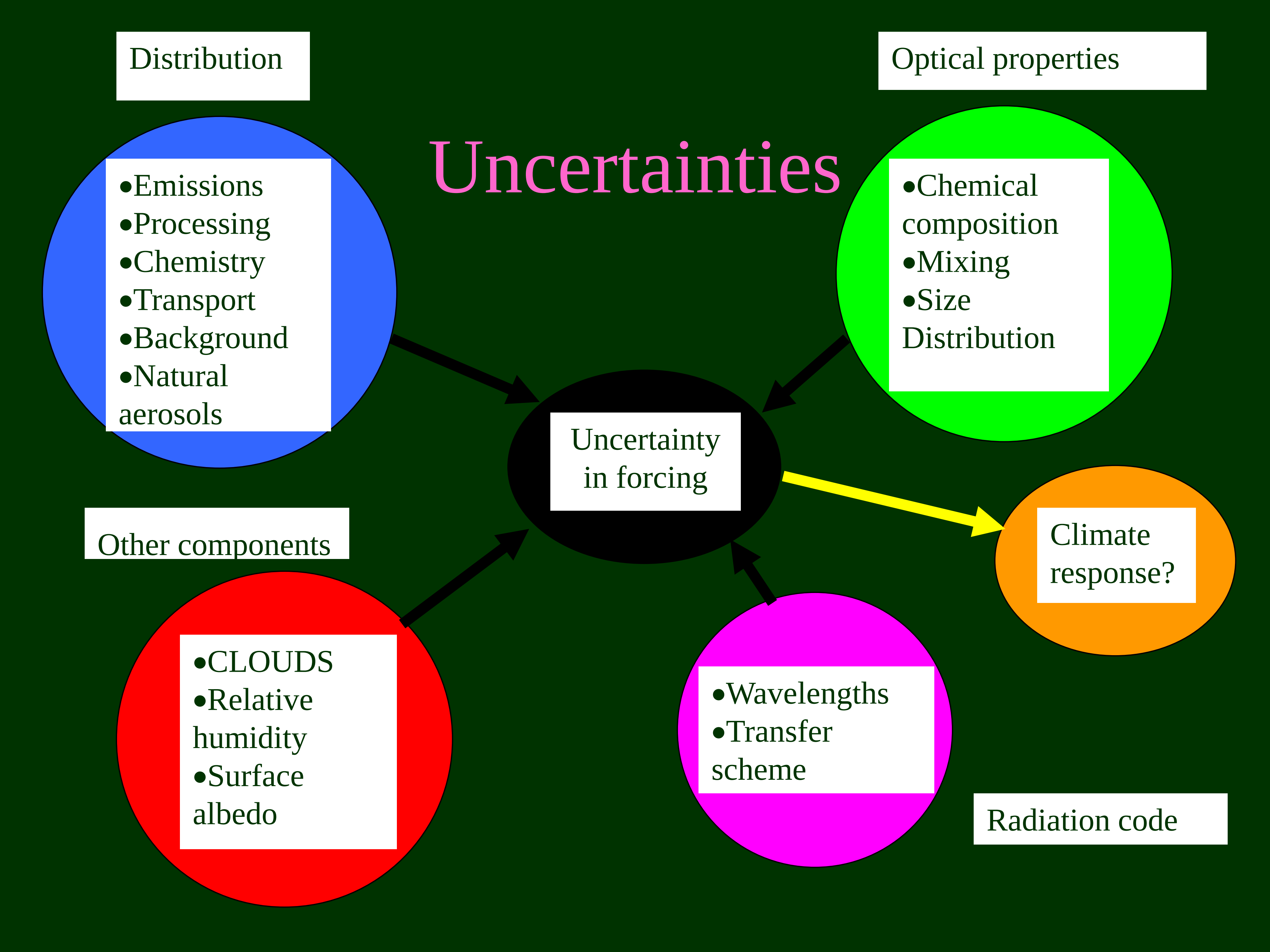


Distribution: Mineral dust

50% of dust burden due to anthropogenic sources due to land use change, overgrazing etc.

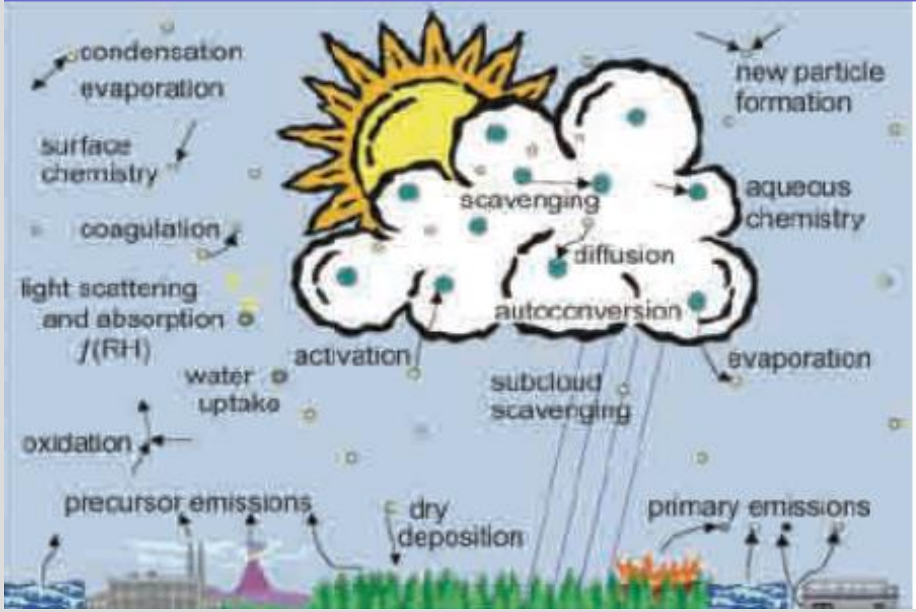
(f)




Uncertainties
Distribution
•Emissions
•Processing
•Chemistry
•Transport
•Background
•Natural aerosols
Optical properties
•Chemical composition
•Mixing
•Size Distribution
Uncertainty in forcing
Climate response?
Other components
•CLOUDS
•Relative humidity
•Surface albedo
•Wavelengths
•Transfer scheme
Radiation code

Aerosol processes and challenges

Major aerosol properties relevant to their impact on climate (US CCSP 2009)



Quantifying the RF of tropospheric aerosols is difficult:

- Different types (sources, emissions, physical and chemical processes, size)
- Short lifetime (up to a week)
- Heterogeneity and discontinuity of sources, varying transport pathways
- Aging during transport
- Anthropogenic vs. natural aerosols, scattering vs. absorbing aerosols,

Those pesky aerosols…

sulfate, dust, seasalt, carbonaceous aerosols

Paul Ginoux (GFDL/NOAA)

Measuring aerosol effects on climate

- Measure effect on radiation at top of atmosphere and surface.
- "Radiative effect" : effect of having aerosol in the present day atmosphere
- "Radiative forcing": effect of changes in aerosol on radiation budget over a given period of time

Global and annual mean radiative forcing can be related to a global and annual mean change in surface temperature using:

$$\Delta T = \lambda \, \Delta F$$

Aerosols alter the water and energy balance

Direct Effect (radiation)

Indirect Effects (microphysics)

Backscattering

Absorption
(column warming)

Forward scattering

Dimming at the surface
(cooling)

Cloud evaporation
(semi-direct effect; warming)

Indirect effects (cooling):

- $\uparrow$ cloud droplet number concentration & $\downarrow$ size if LWC remains unchanged (1st indirect, cloud albedo)
- $\downarrow$ rain by $\downarrow$ coalescence efficiency and $\uparrow$ cloud lifetime (2nd indirect, cloud lifetime)

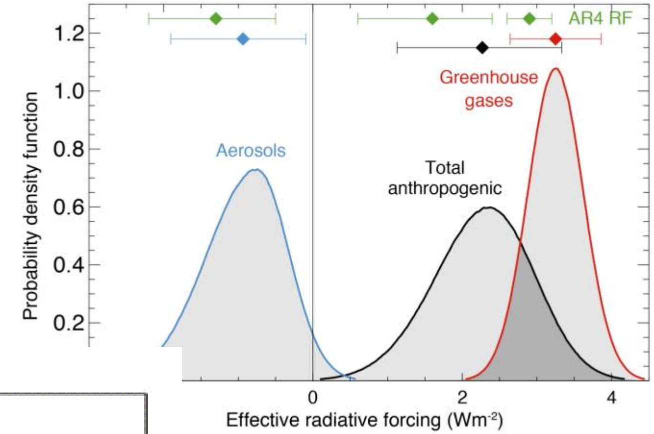
The effects of anthropogenic aerosols on long-wave radiation are relatively minor (except for desert dust)

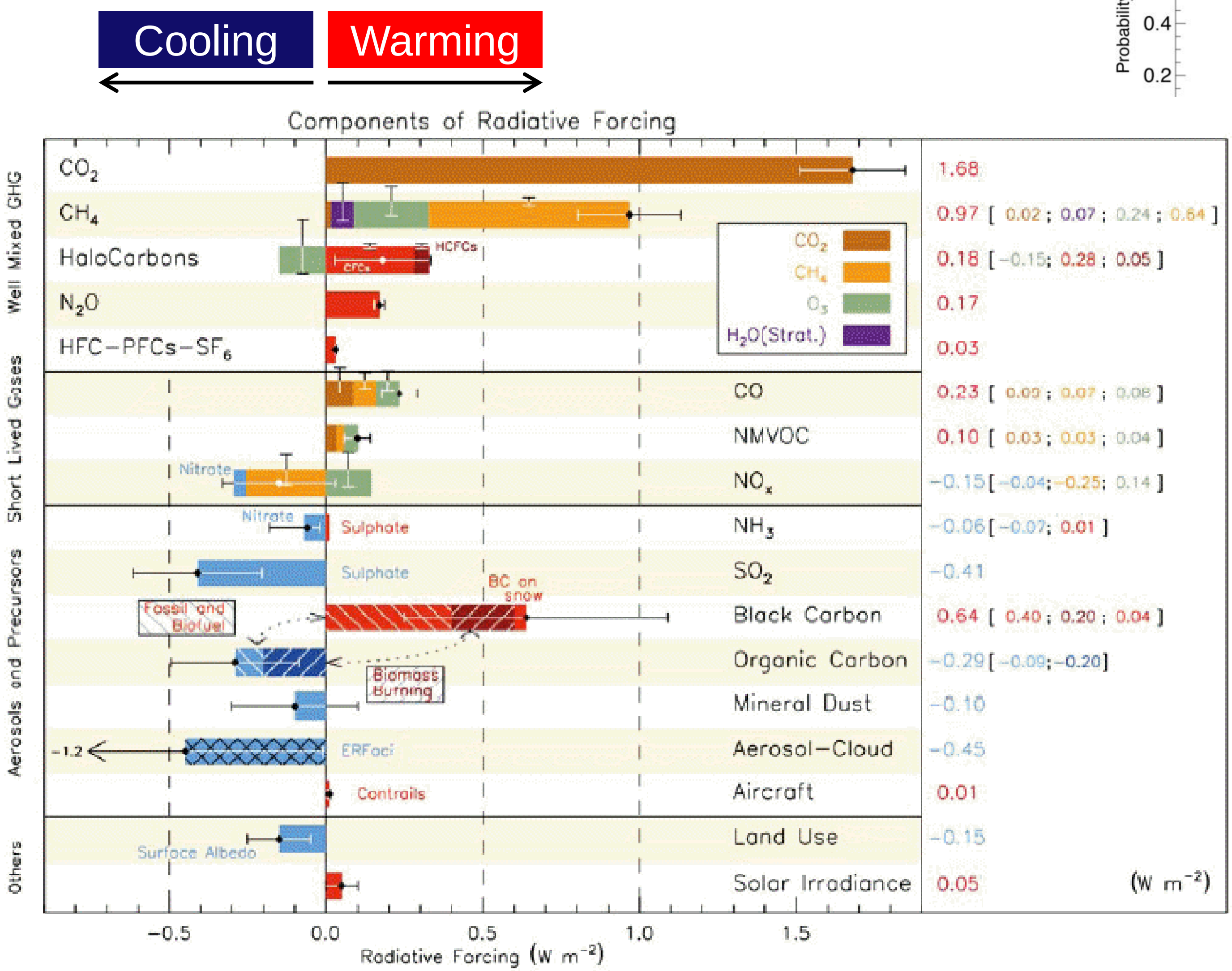
Differential heating/cooling atmosphere/surface → vertical stability and convective potential of the atmosphere → anomalous circulation with feedbacks on **water & energy cycles**

Clouds over the Equatorial Indian Ocean (Feb. 1999; Ramanathan et al. 2001)

Do aerosols really matter for climate?

IPCC 2013

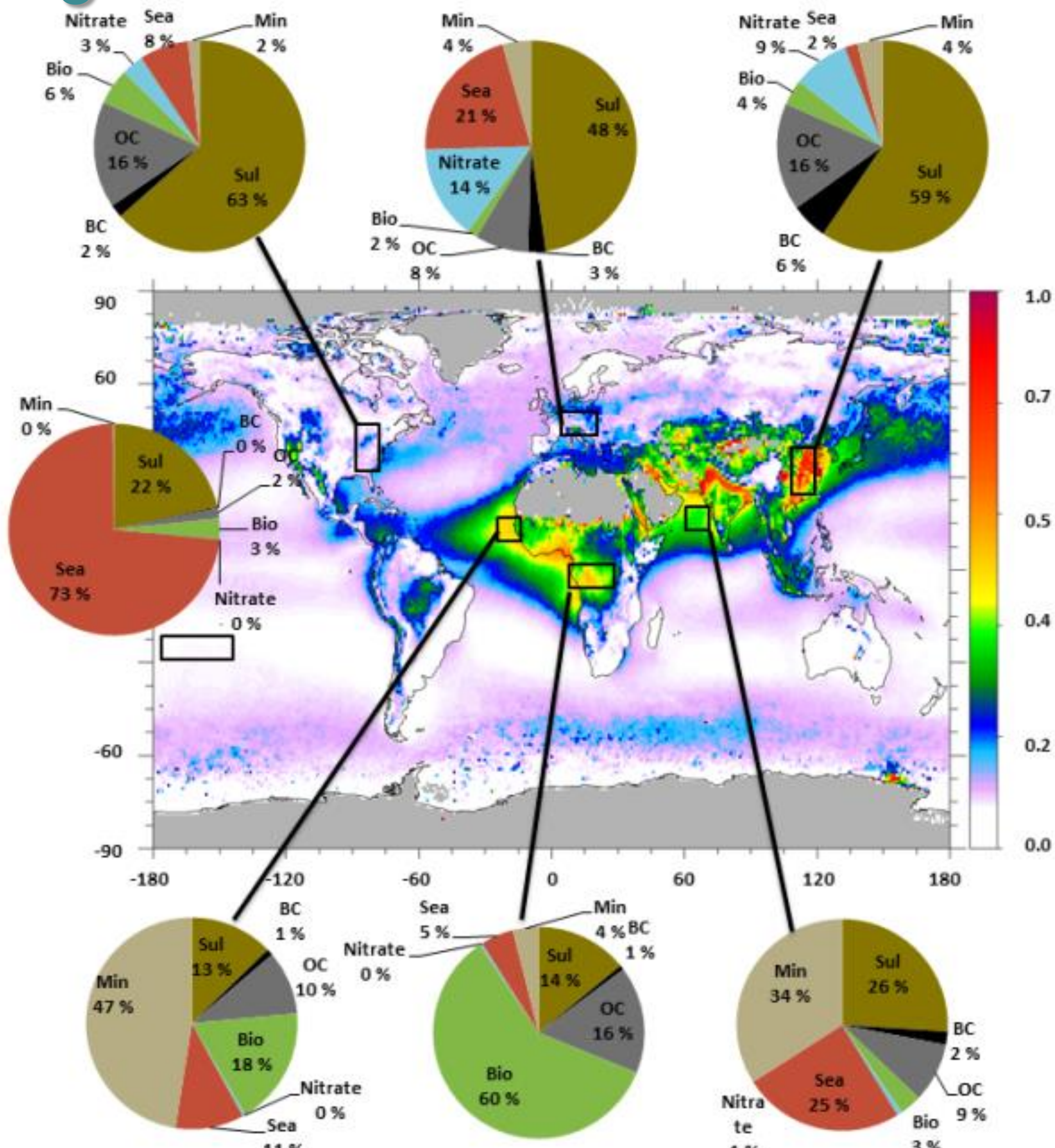




The Aerosol Challenge

Aerosols: alter atmospheric/surface heating gradients, diabatic heating from rainfall

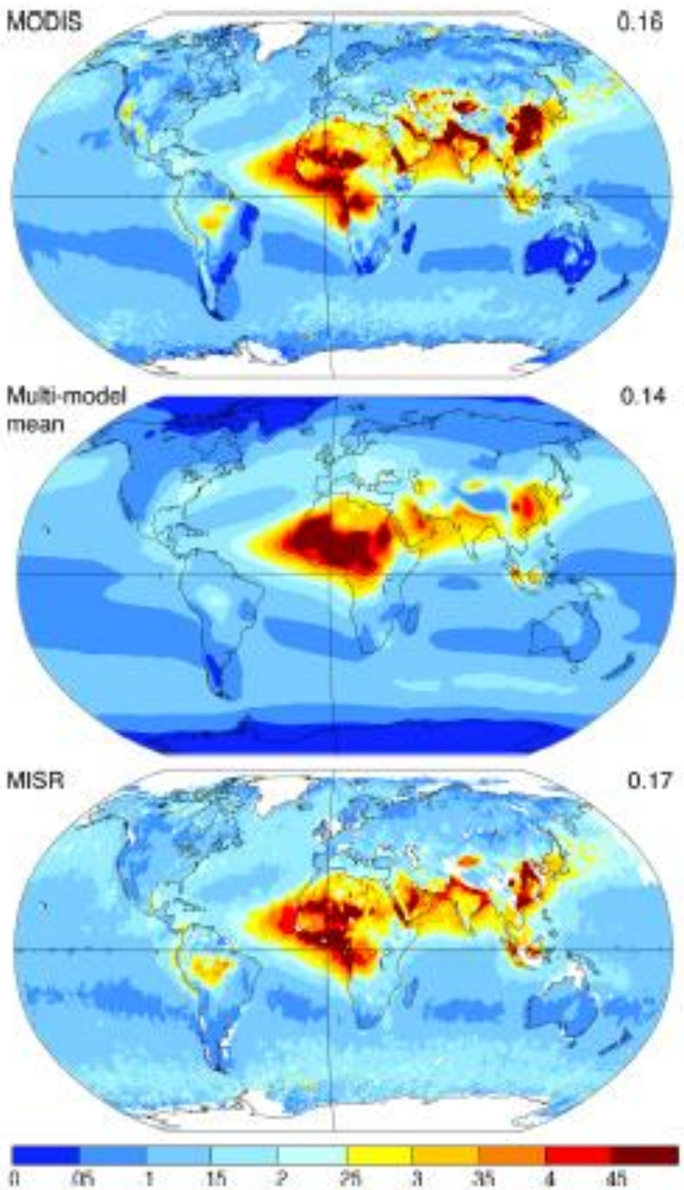
ACC: Aerosol-Circulation-Climate (across scales)

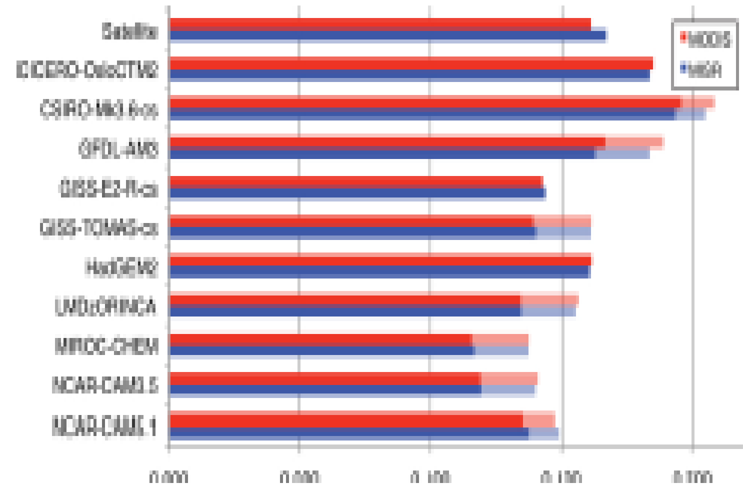


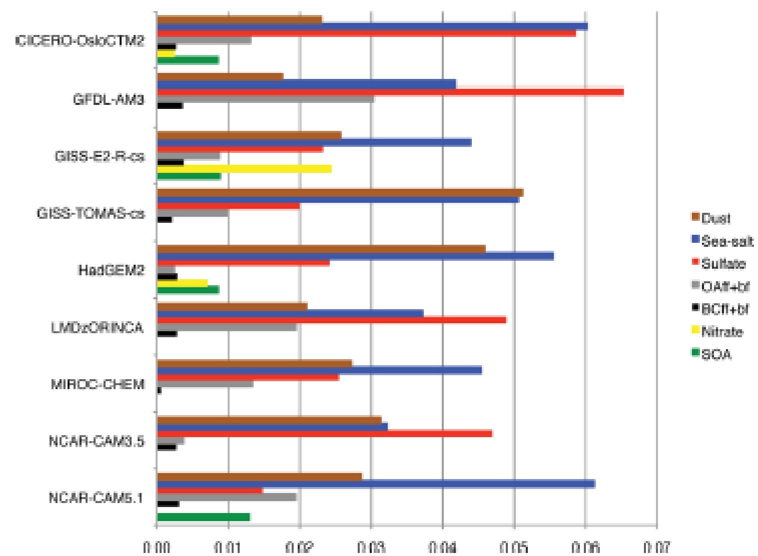
MODIS AOD (2001–2010), % aerosol types (Myhre et al. 2013)

Present-day aerosols in models (ACCMIP)

AOD at 550 nm

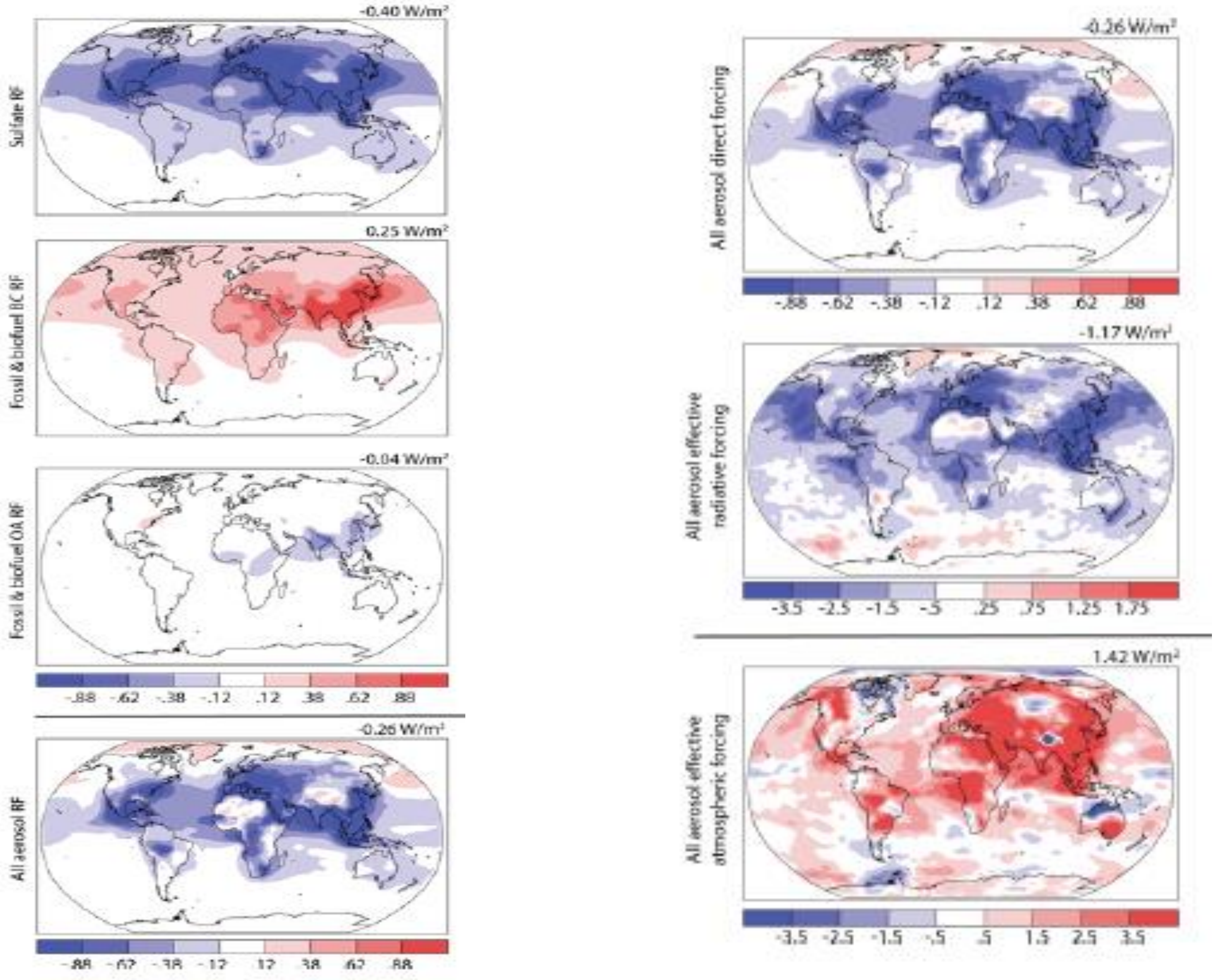




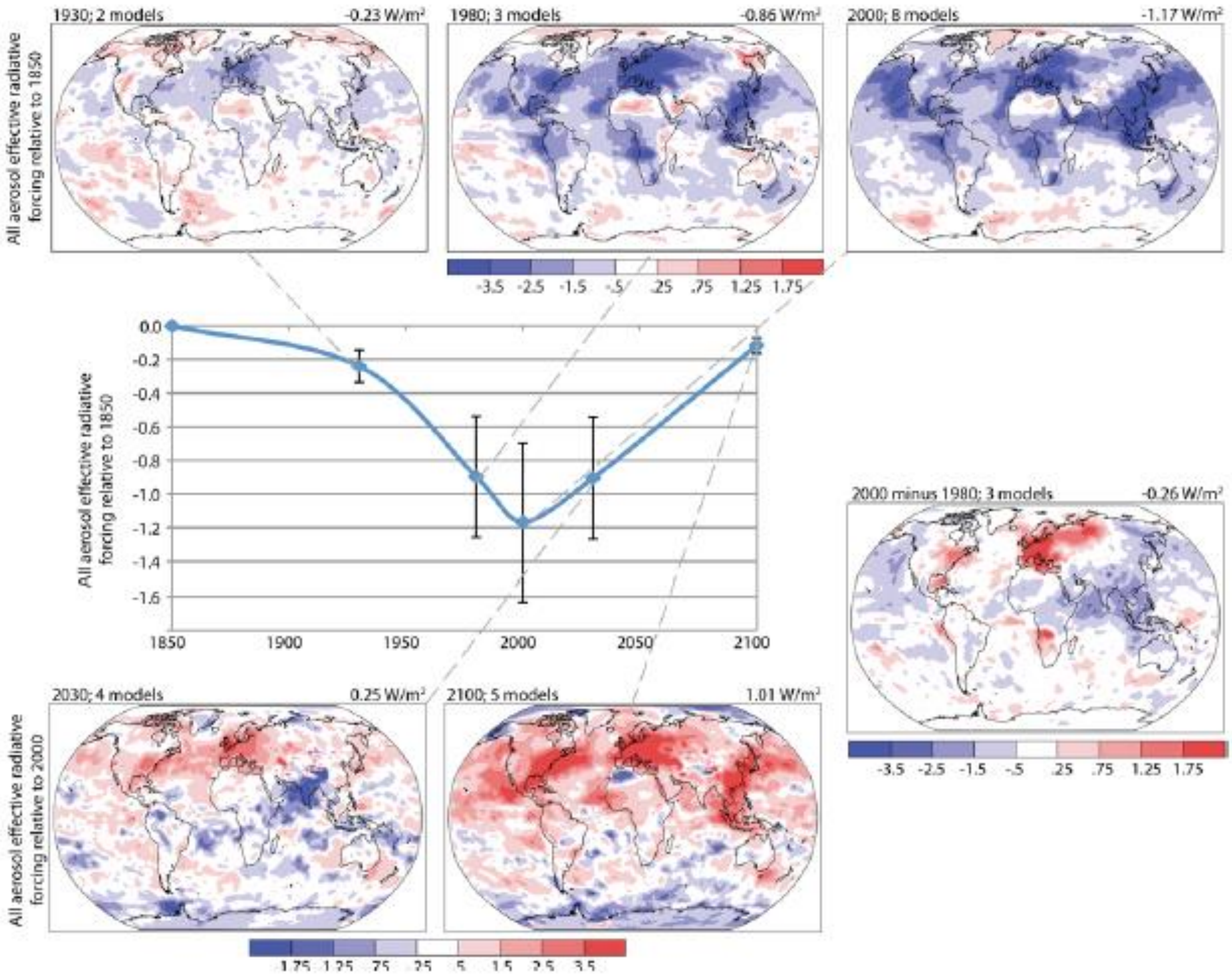


Shindell et al. 2013

Distribution of radiative forcing



Temporal variation of radiative forcing



AERONET – AEROsol Robotic NETwork

AERONET: an optical ground based aerosol monitoring network and data archive supported by NASA's EOS and expanded by many other institutions. Identical automatic sun-sky scanning spectral radiometers owned by national agencies and universities.

Data from this collaboration provides globally distributed near real time observations of aerosol spectral optical depths, aerosol size distributions, and precipitable water in diverse aerosol regimes

India AERONET locations: Kanpur and Gandhi College

Inversion data: size distribution, refractive index, single scattering albedo, asymmetry factor, extinction optical depth

+Home

Aerosol Inversions

+ AEROSOL/FLUX NETWORKS
+ CAMPAIGNS
+ COLLABORATORS
- DATA
+ LOGISTICS
+ NASA PROJECTS
+ OPERATIONS
+ PUBLICATIONS
+ SITE INFORMATION
+ STAFF
+ SYSTEM DESCRIPTION

AERONET DATA ACCESS
DATA SYNERGY TOOL

AERONET Data Display Interface

Version 2 Inversions

Site: Kanpur - Additional Site Information

DISCLAIMER	AERONET Level 1.5. Real Time Cloud Screened data. The following AERONET data are automatically cloud cleared but may not have final calibration applied. These data are not Quality Assured.

The principal investigator(s) of the 'Kanpur' site:
Brent Holben
S. N. Tripathi
If you intend to use the following data please contact principal investigator(s) via e-mail:
Brent.N.Holben@nasa.gov
snt@iitk.ac.in

Operational Time at 'Kanpur' Site
5168 Days [14.159 Years]
Start Date: 22-JAN-2001; Latest Date: 16-JUL-2016

Total Processed Data [Years represent total data equivalent]
Level 1.0 AOD: 4484 Days [12.285 Years]
Level 1.5 AOD: 4170 Days [11.425 Years]
Level 2.0 AOD: 3332 Days [9.129 Years]

Return to the World Map | Switch to Version 2 Direct Sun | Switch to Version 1 Direct Sun and Inversions

Data Display Controls

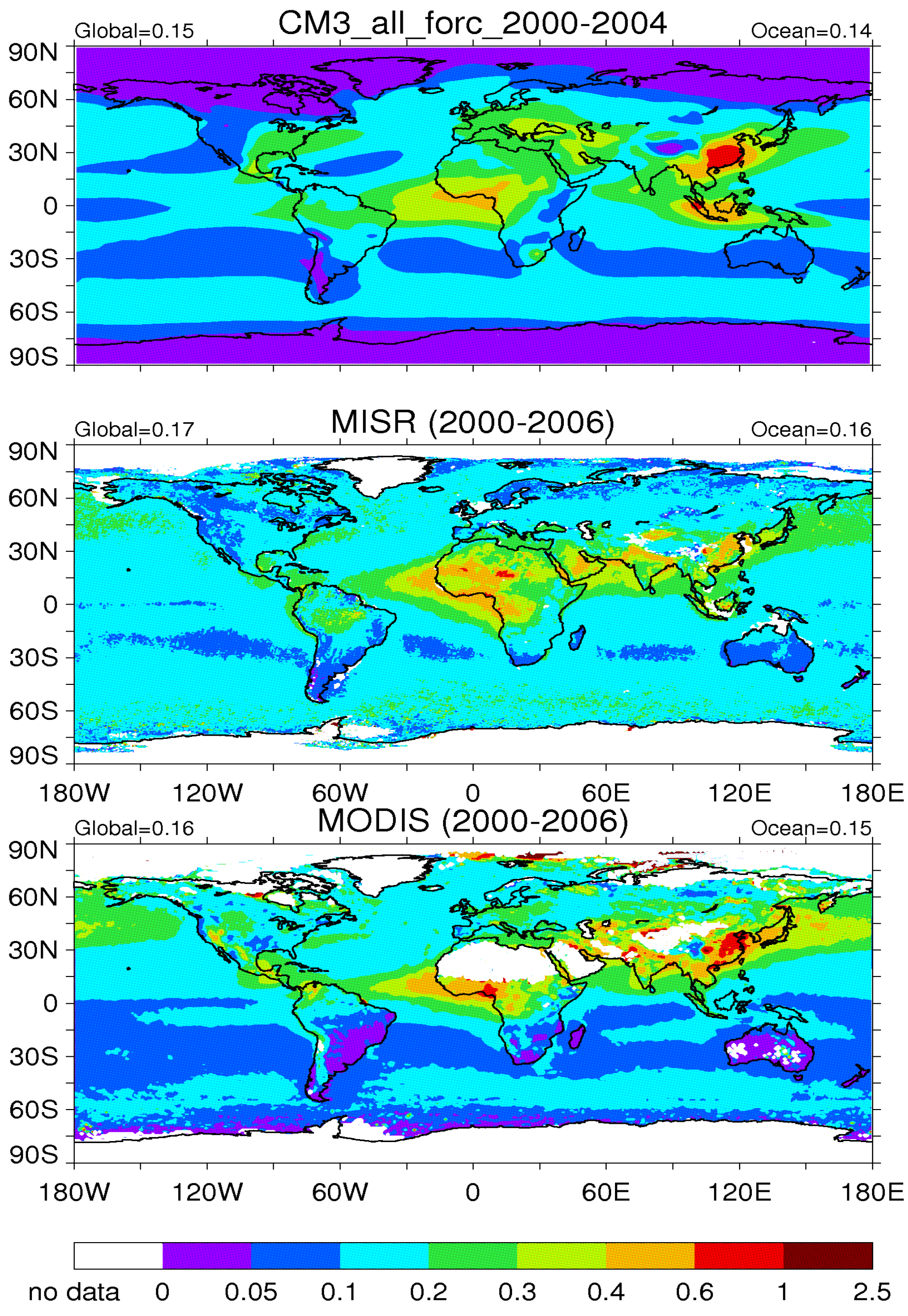
AERONET Inversion Data Product:
- Size Distribution
- Refractive Index (Real)
- Refractive Index (Imaginary)
- Absorption Optical Depth

Inversion Level (2016): Level 1.5

SELECT CHARTS FOR LARGER IMAGES

Related Product Availability for Kanpur (select each day below):
- Back Trajectory Analyses - Availability - More Information
- MPLNET Images - Availability - More Information
- Show TERRA-MODIS | AQUA-MODIS Rapid Response Images - Availability - More Information
- LandSat Image
- Visible Satellite Images (Check Availability) - More Information
- Infrared Satellite Images (Check Availability) - More Information

GFDL CM3 evaluation

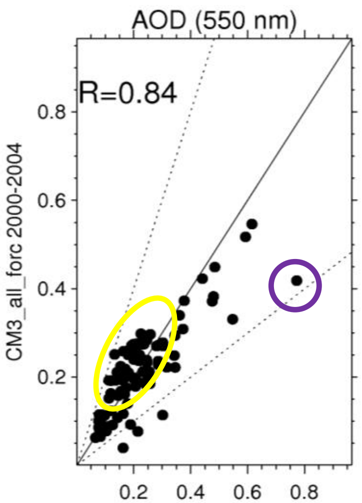


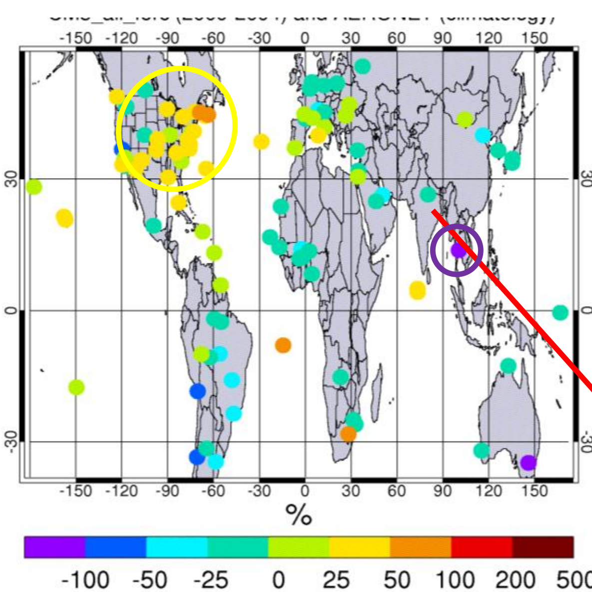
MAM

- With updated optical properties, new emission inventories, and new physics, CM3 simulates the AOD with spatial distribution in agreement with MODIS and MISR
- CM3 underestimates AOD in polar regions
- Larger errors are located over land (e.g., over industrialized countries in the midlatitudes)

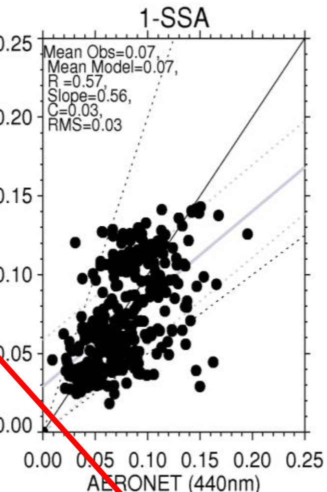
CM3 aerosols compared to surface observations

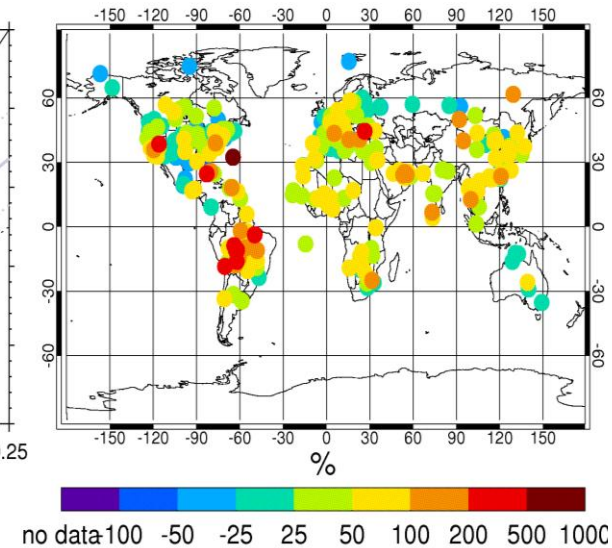
(CM3-AERONET)/AERONET (2000-2004)





Co-albedo a measure of aerosol absorption

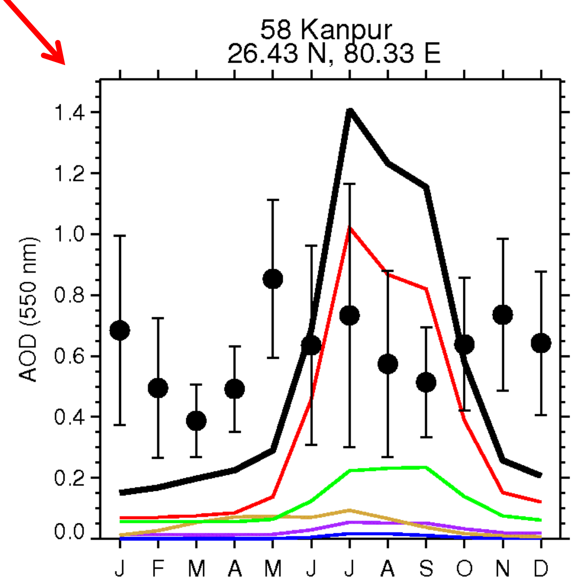




AOD: within +-25% of AERONET, ~+50% over US East Coast
(~-50% over Mega-cities, e.g. Bangkok)

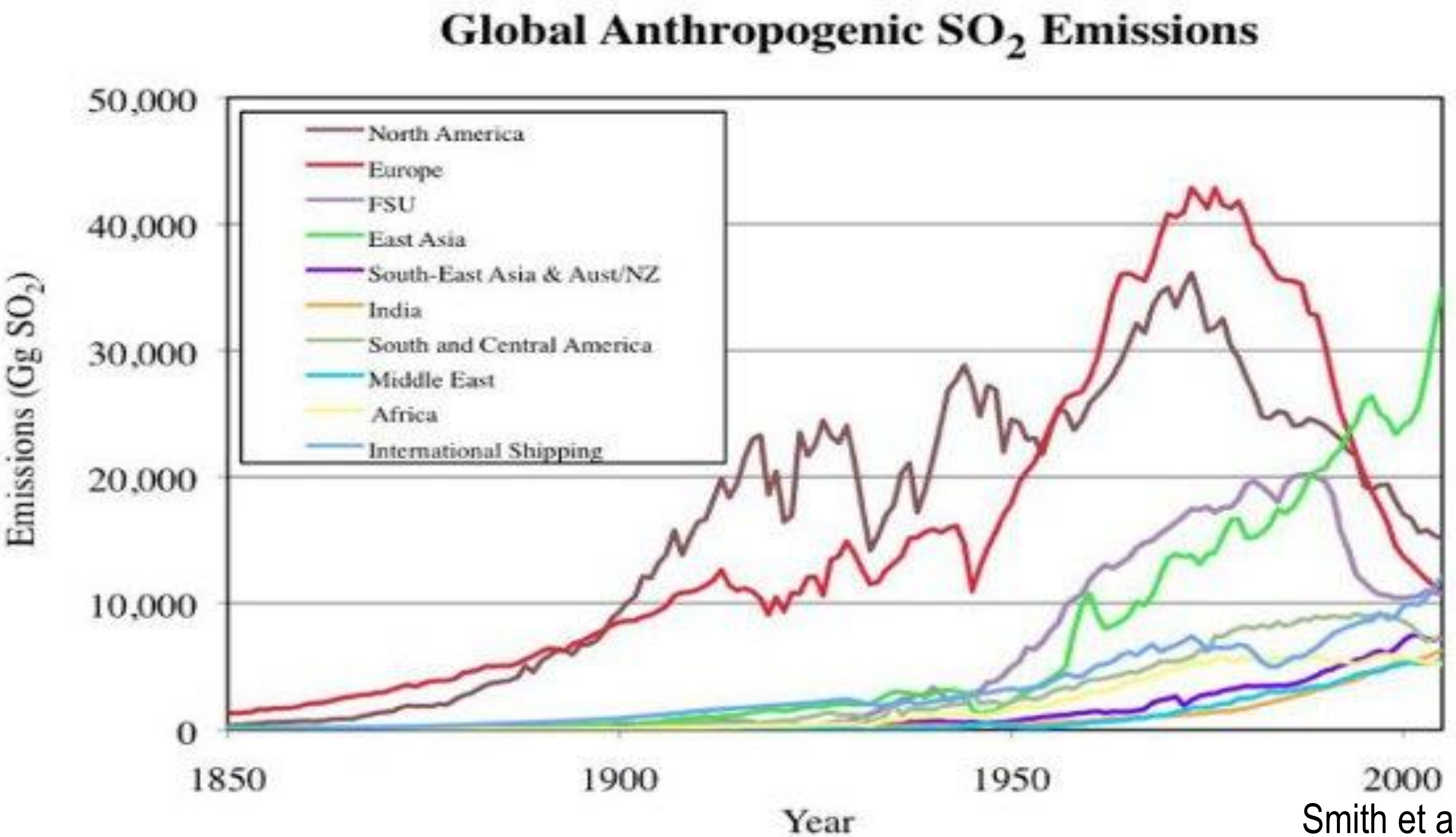
1-SSA: slightly overestimated, but within a factor 2 (but CM3 is at 550nm, AERONET at 440nm: + bias in bb regions)

Winter and spring (summer) AOD at Kanpur underestimated (overestimated): dust, BC



AERONET
CM3: SO_4, BC, OC, Dust

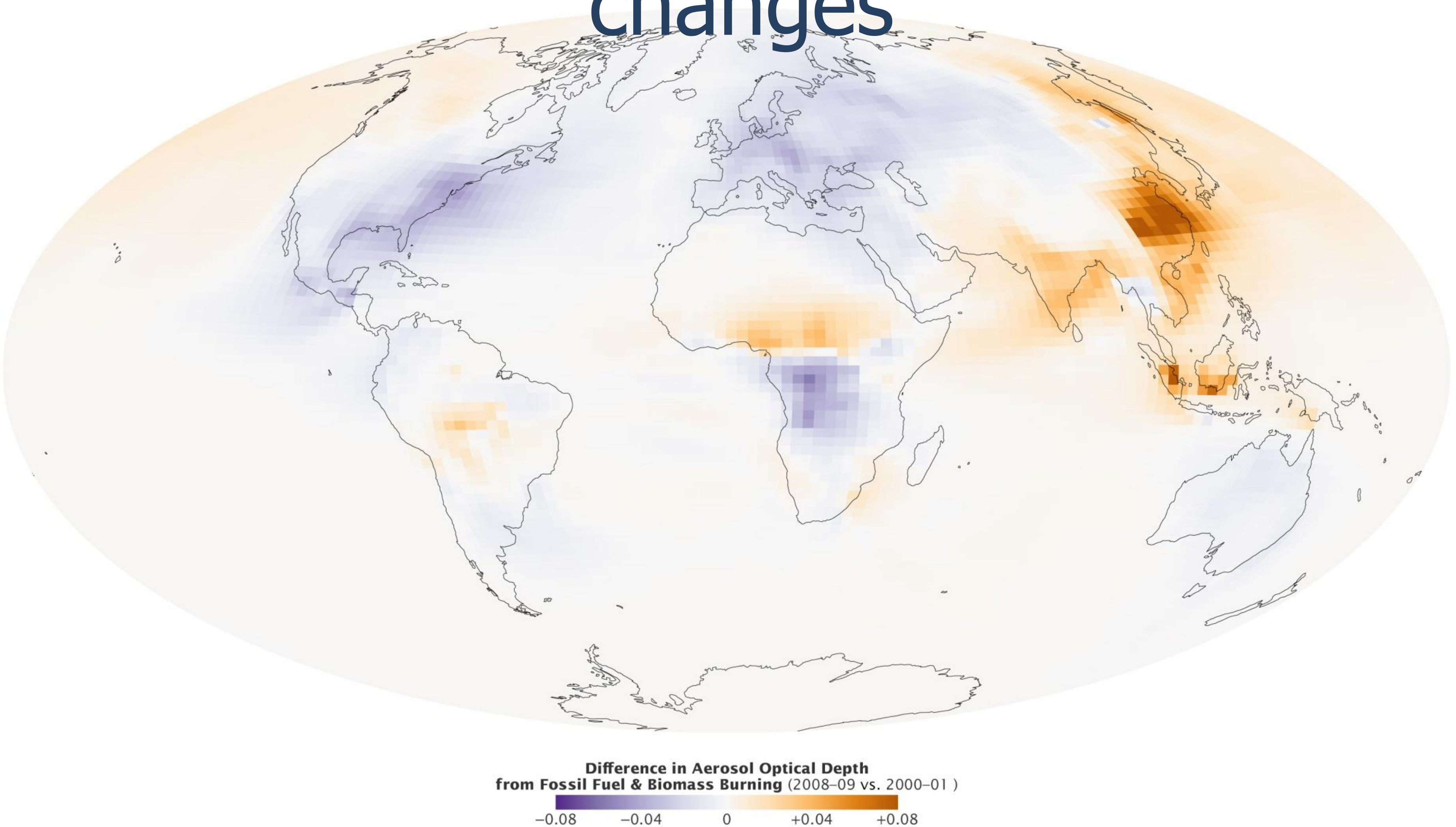
Different temporal variability in aerosol emissions



Smith et al. 2011

What is the impact of the emission shift?

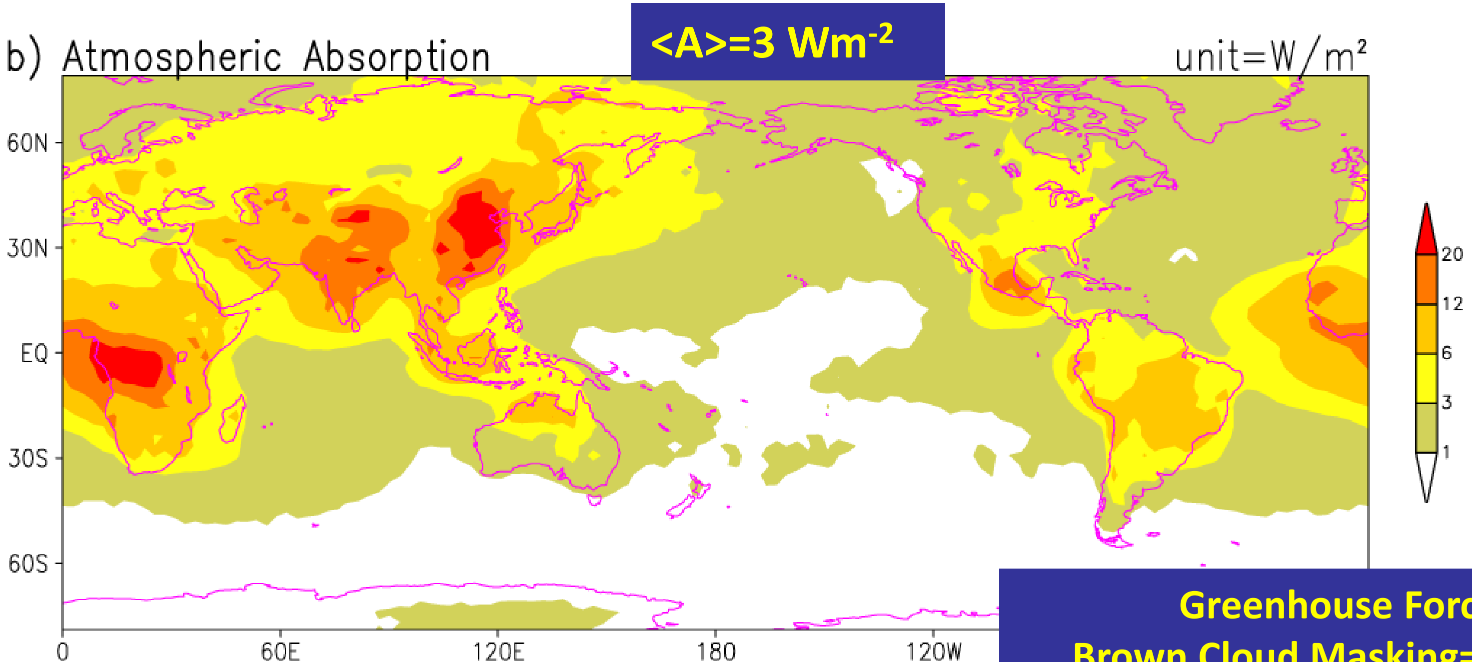
A contrasting pattern of aerosol changes



Changes in anthropogenic aerosols between 2000–01 and 2008–09

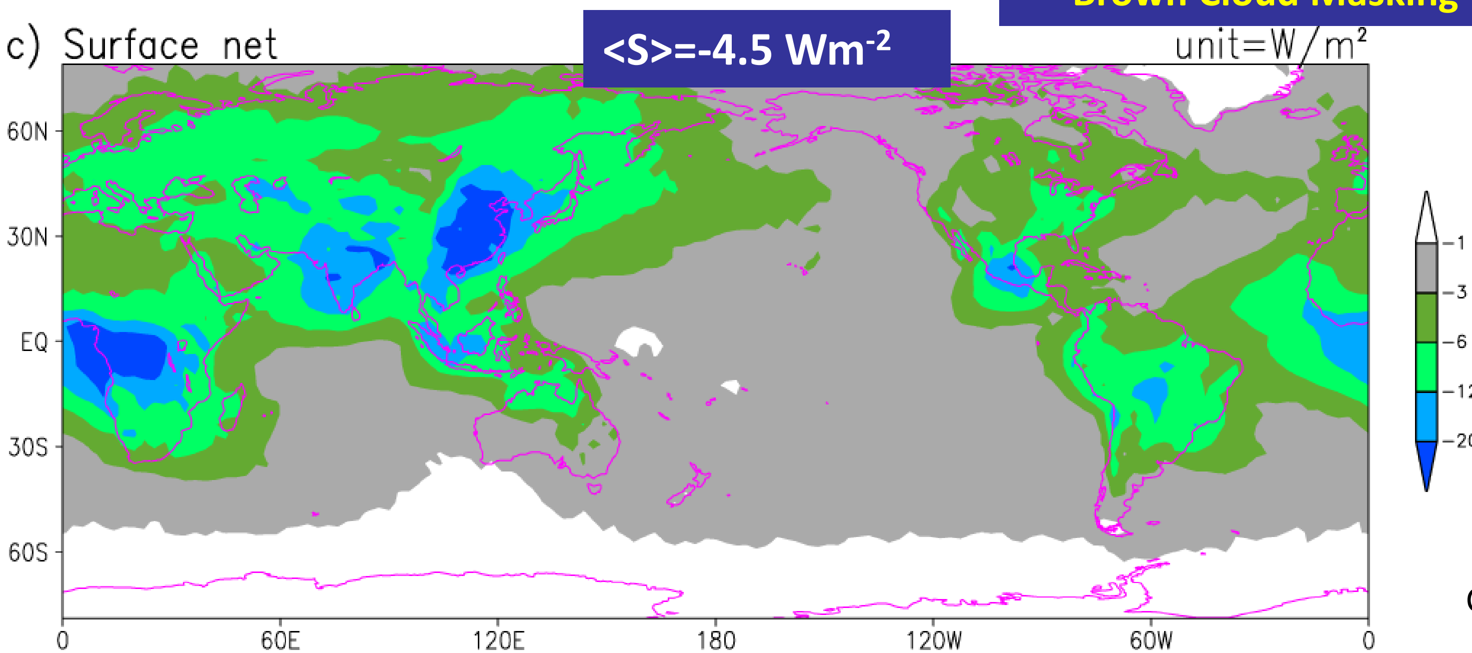
(Chin et al. 2014)

Surface Dimming & Atmospheric Heating by Brown Clouds: annual mean 2001-2003



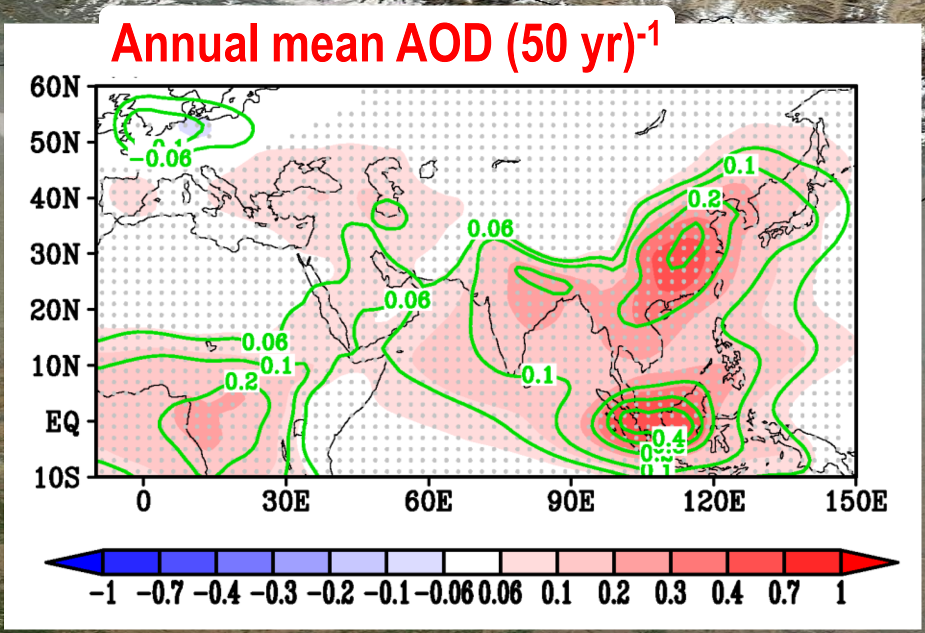
Greenhouse Forcing = 3 Wm^{-2}

Brown Cloud Masking= -1.5 (± 50%) Wm^{-2}

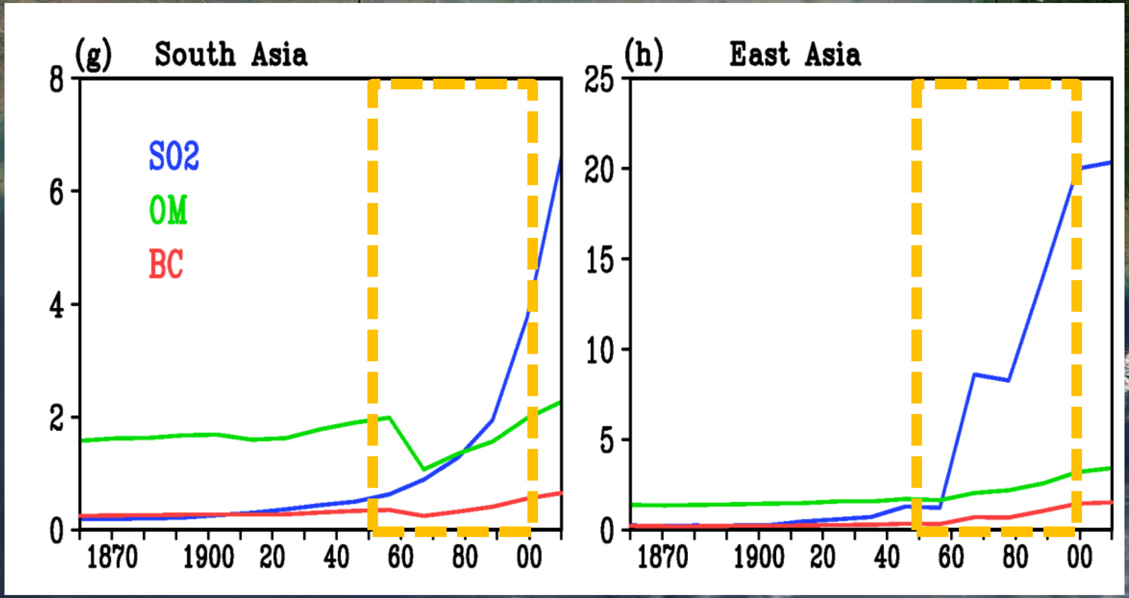


Chung et al. (2005)

Widespread aerosols over South Asia



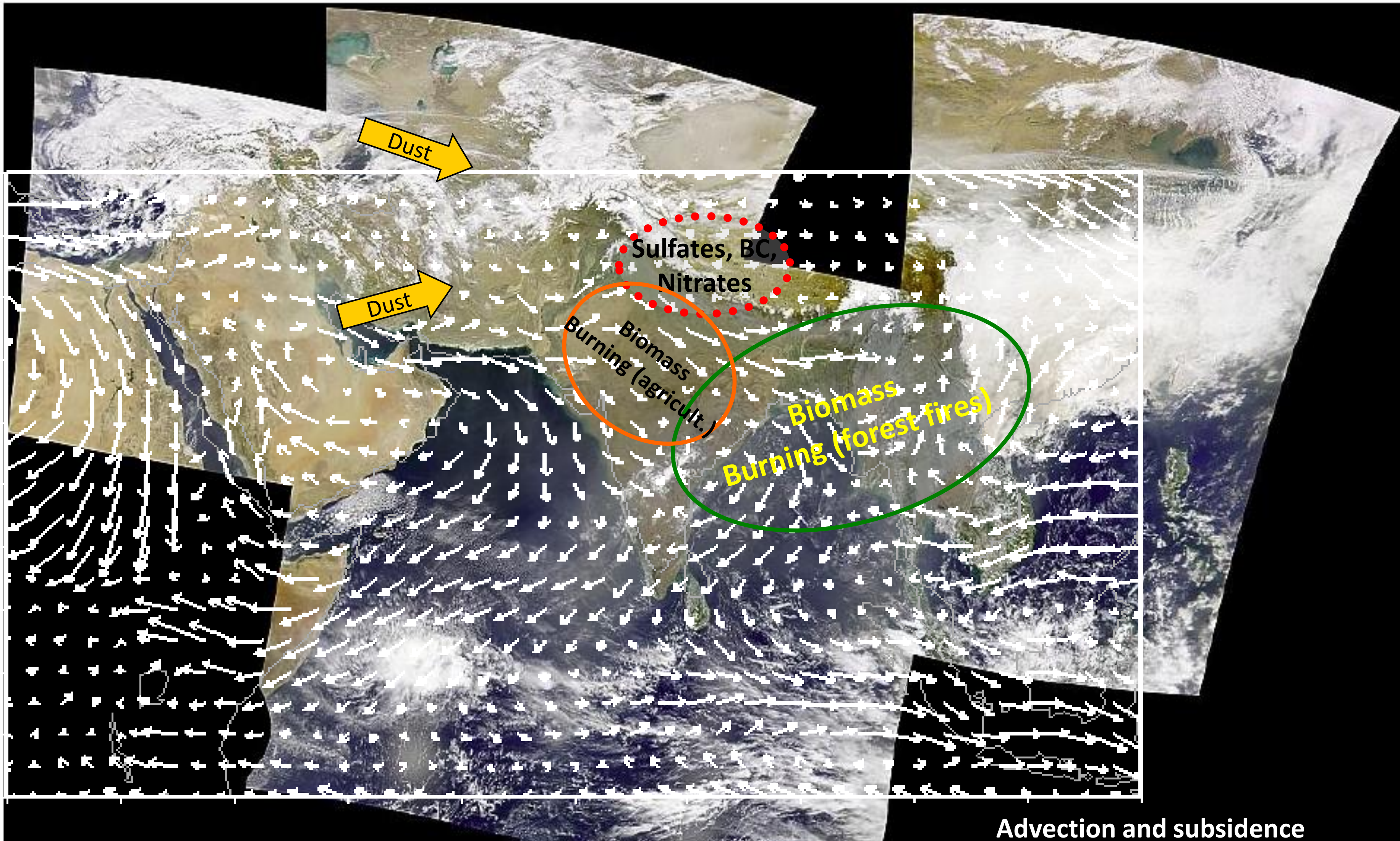
Emission increase (*x*-fold)		
	South Asia	East Asia
SO_2	*10*	*16*
BC	*2*	*5*



MODIS Land Rapid Response Team, NASA/GSFC

Data from Lamarque et al. 2010

Widespread aerosols over South Asia

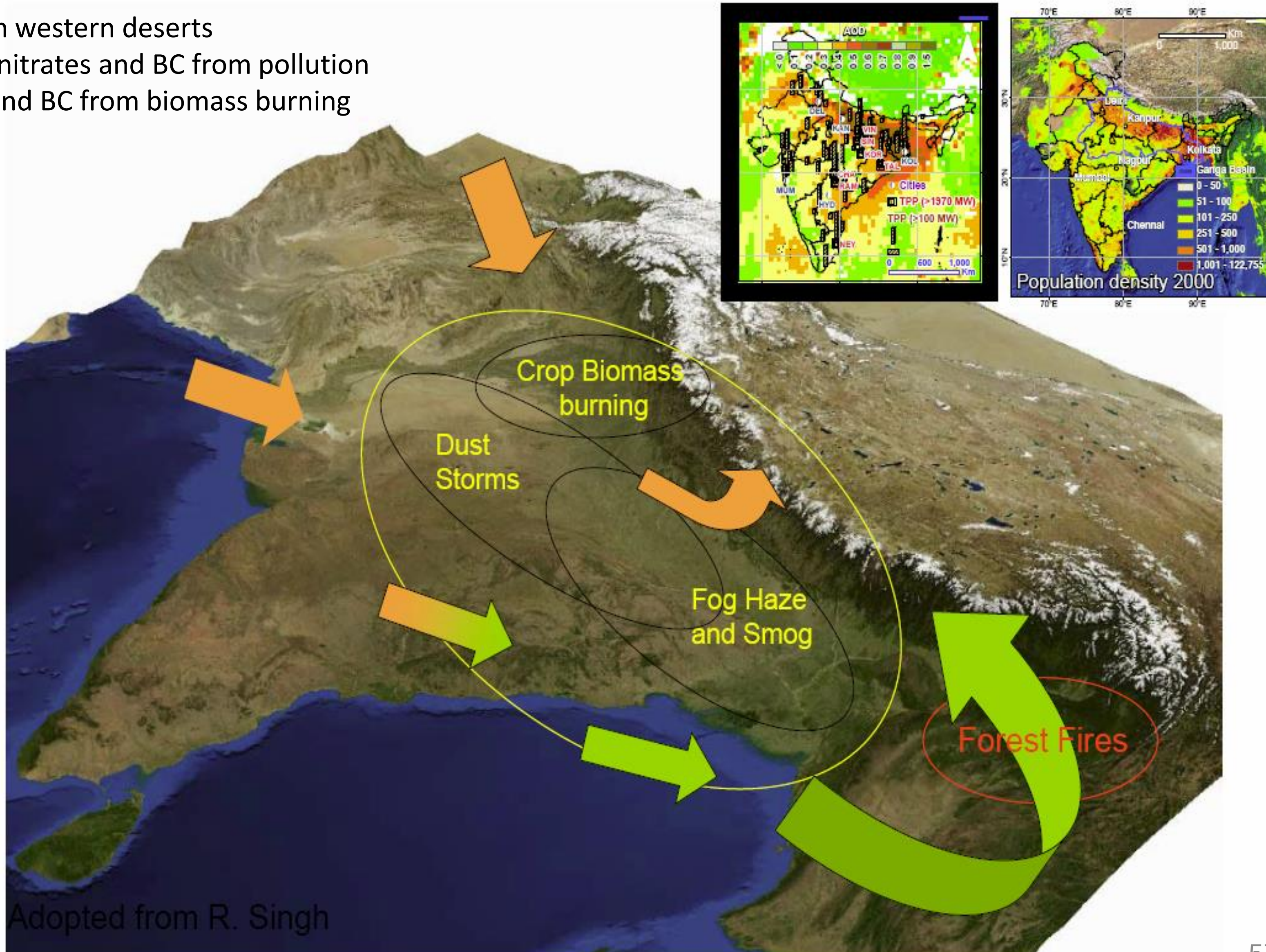


Satellite image taken on March 21, 2001 (Ramanathan and Crutzen, 1999)
& 850-hPa wind from ERA-40 for March 2001

Aerosols over the Indo-Gangetic Plain (IGP)

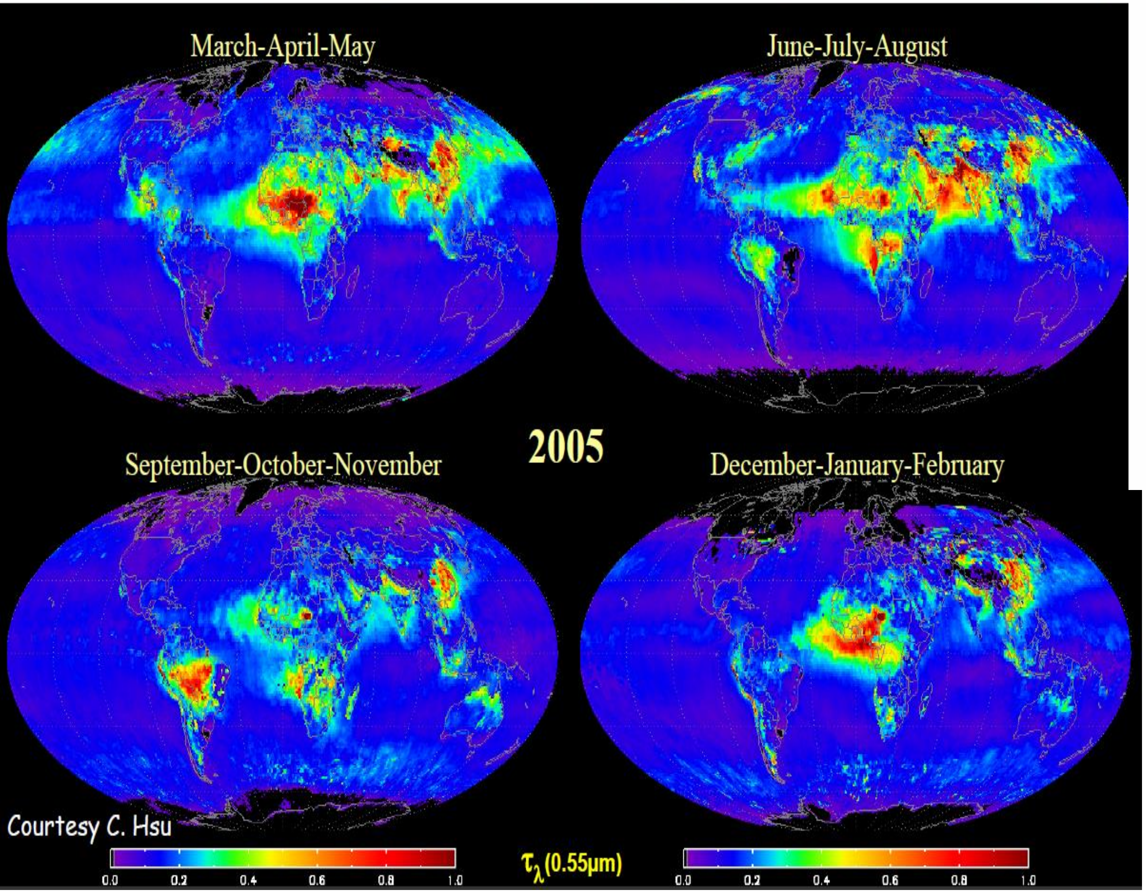
The IGP is one of the largest populated basins of the world

Dust from western deserts
Sulfates, nitrates and BC from pollution
Organic and BC from biomass burning

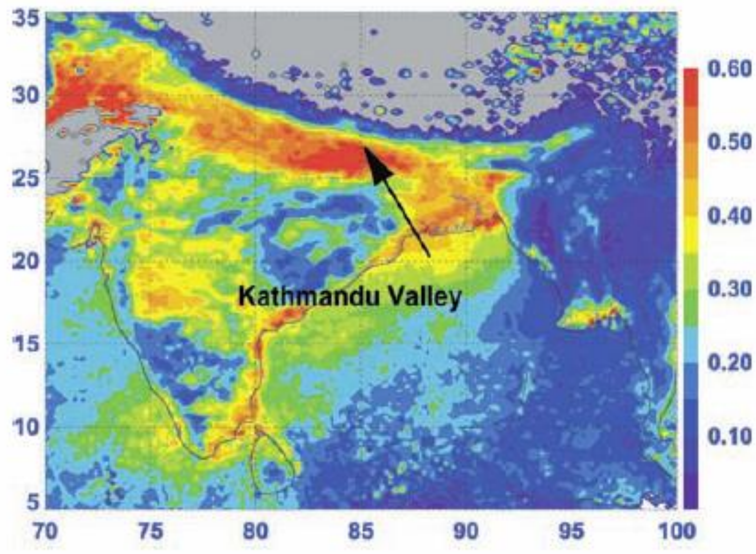


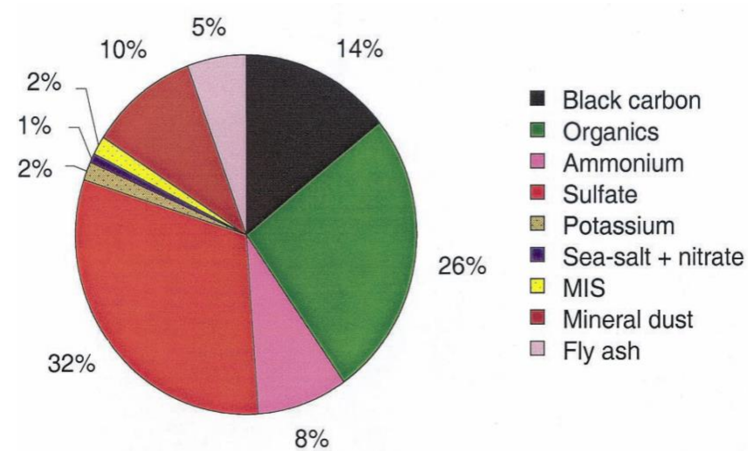
Aerosols Hotspots

- ***Year-round aerosols***
  - East-Southeast China, *mega-city/smoke*
  - Indo-Gangetic Plain, *mega-city/dust*
  - Africa, Saharan dust (less in SON)
- ***Seasonal aerosols***
  - East Asia, dust (MAM)
  - Southwest Asia, dust (JJA)
  - Southeast Asia, smoke (DJF-MAM)
  - S. America, smoke (JJA-SON)
  - Africa, smoke (SON-DJF)
  - Southwest Asia, haze (MAM)



MODIS AOD for October-May 2001-02
(Ramanathan and Ramana. 2005)

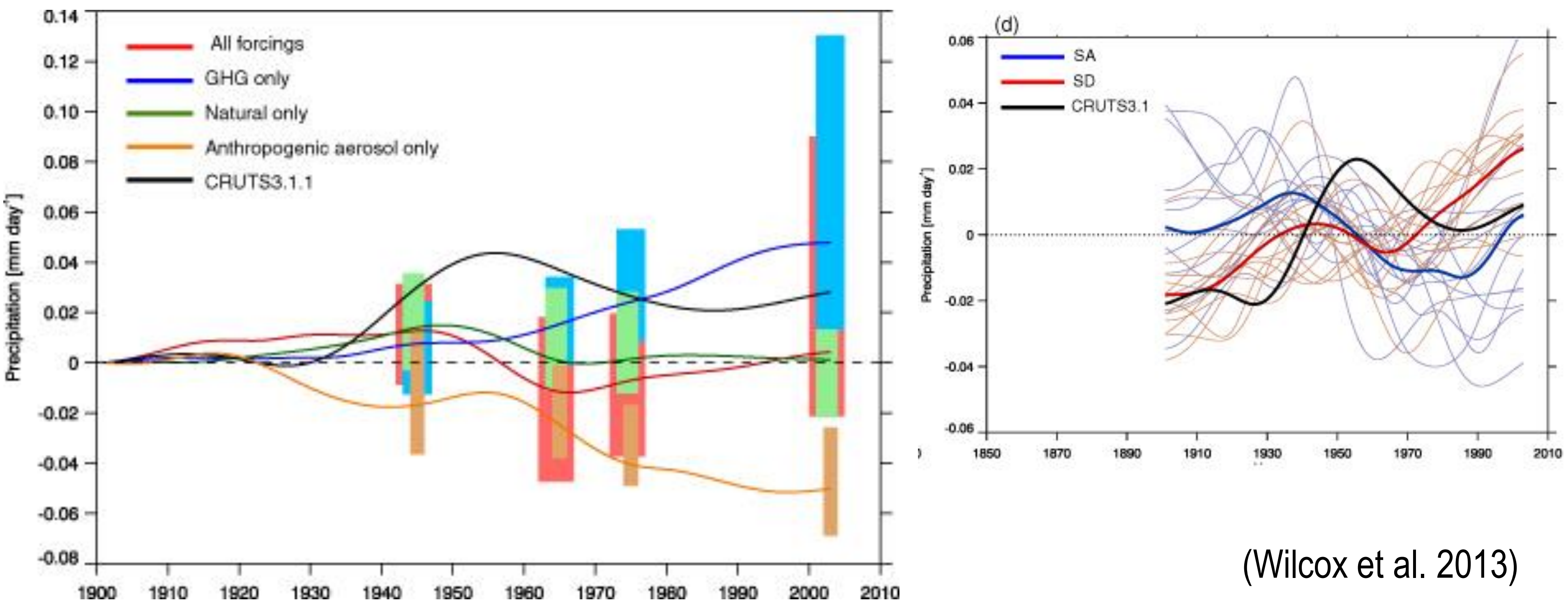




Average mass fractions of **fine** aerosols (Feb-Mar 1999 over the Indian Ocean. Error: ±20% (Ramanathan et al., 2001)

Yes, all this is OK. But what are, if any, the impacts of aerosols on climate characteristics closer to my perception?

Influence of anthropogenic aerosols on multi-decadal P variations



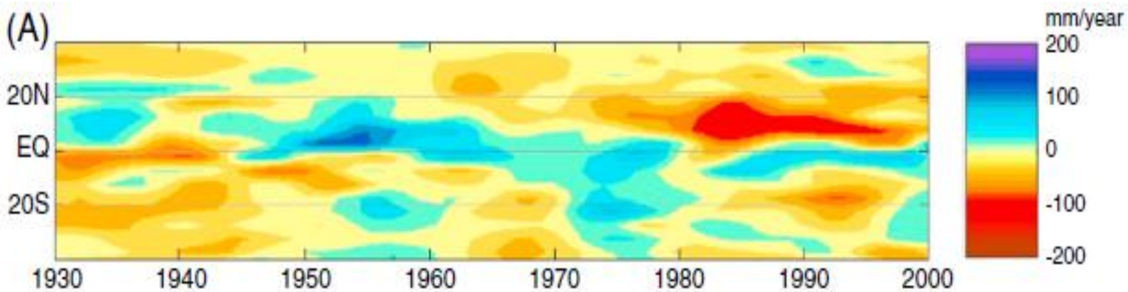
(Wilcox et al. 2013)

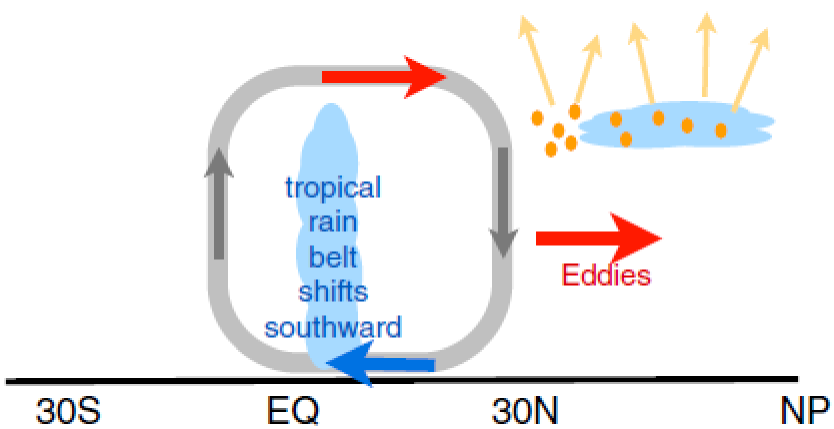
Lack of linearity. Natural and anthropogenic aerosol forcing determine the sign of the trend in land-precipitation in the mid-twentieth century.

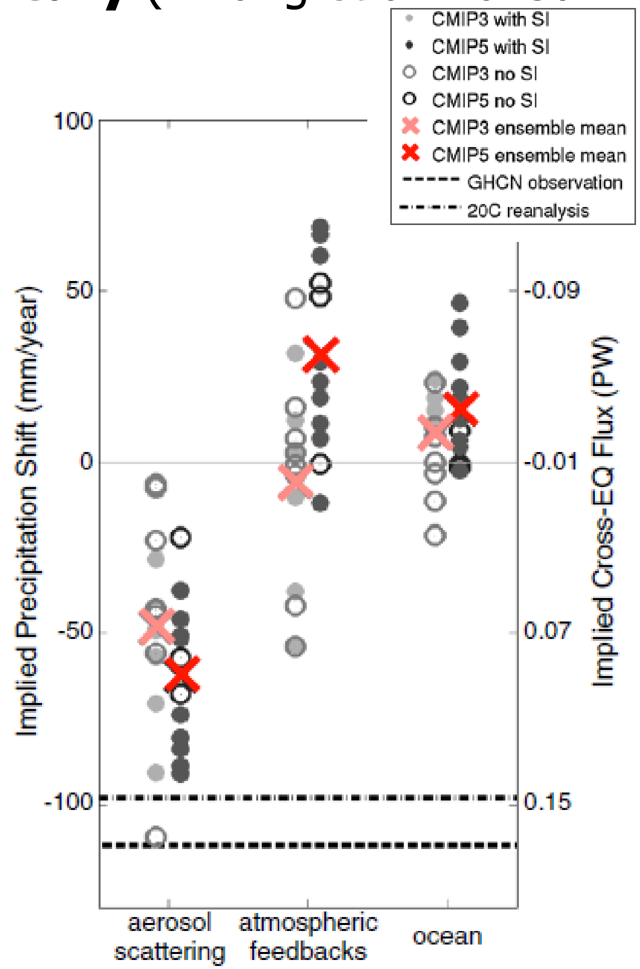
Models with the aerosol indirect effect are able to represent more of the inter-decadal variability in land-only precipitation compared to those without.

Southern shift of the ITCZ

Changes in precipitation during the 20th century (Hwang et al. 2013)



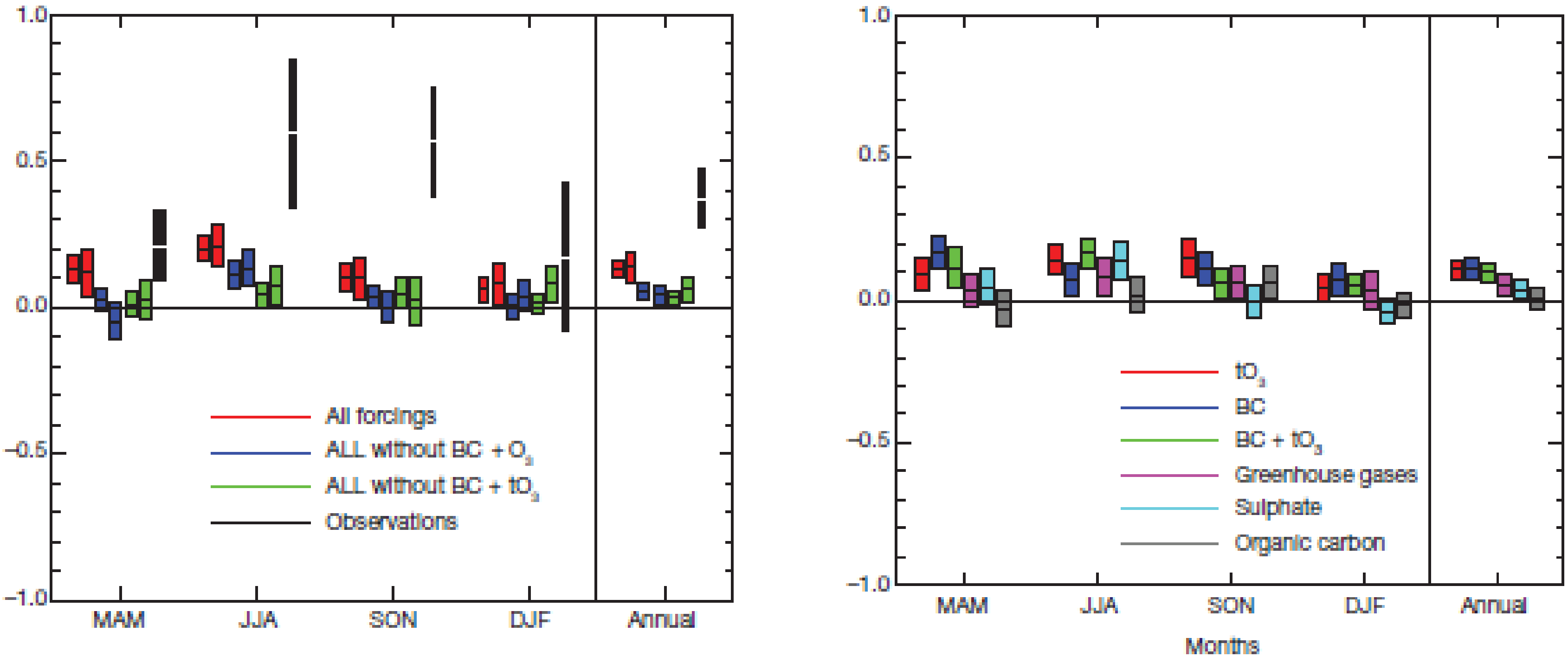




Temperature asymmetries between the hemispheres (NH cooling by sulfates) cause a shift of the ITCZ toward the warmer hemisphere and a strengthening of the Hadley cell in the colder hemisphere

Northern Hemisphere tropical expansion by BC & tO_3

Expansion (°lat per decade) over 1970-2009 (Allen et al. 2012)

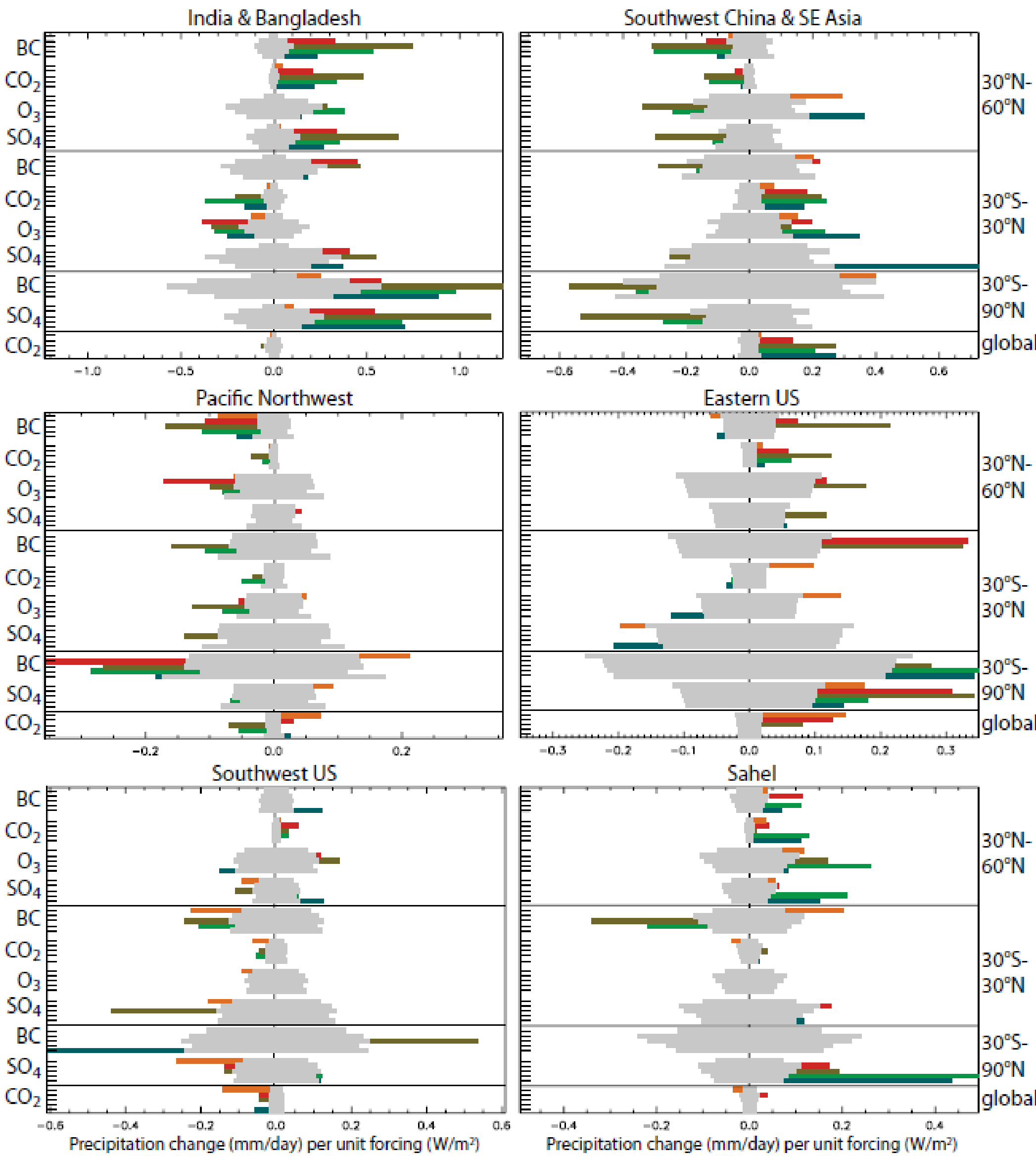


Increases in NH warming agents (BC and tO3) are noticeably better than GHGs at driving expansion, and can account for the observed JJA maximum in tropical expansion.

Atmospheric heating in mid-latitudes generates a poleward shift of the tropospheric jet, the main division between tropical and temperate air masses.

Impact of regional radiative forcing

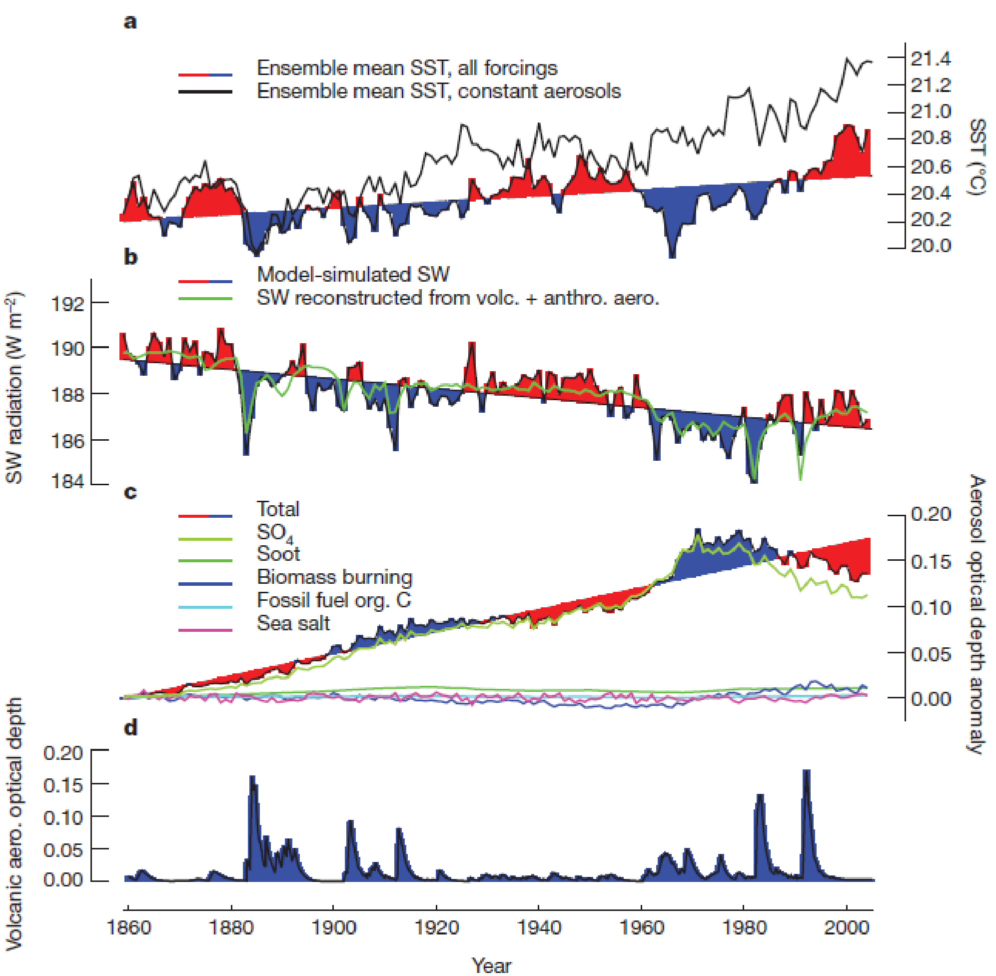
Precipitation response to regional radiative forcing (Shindell et al. 2012)

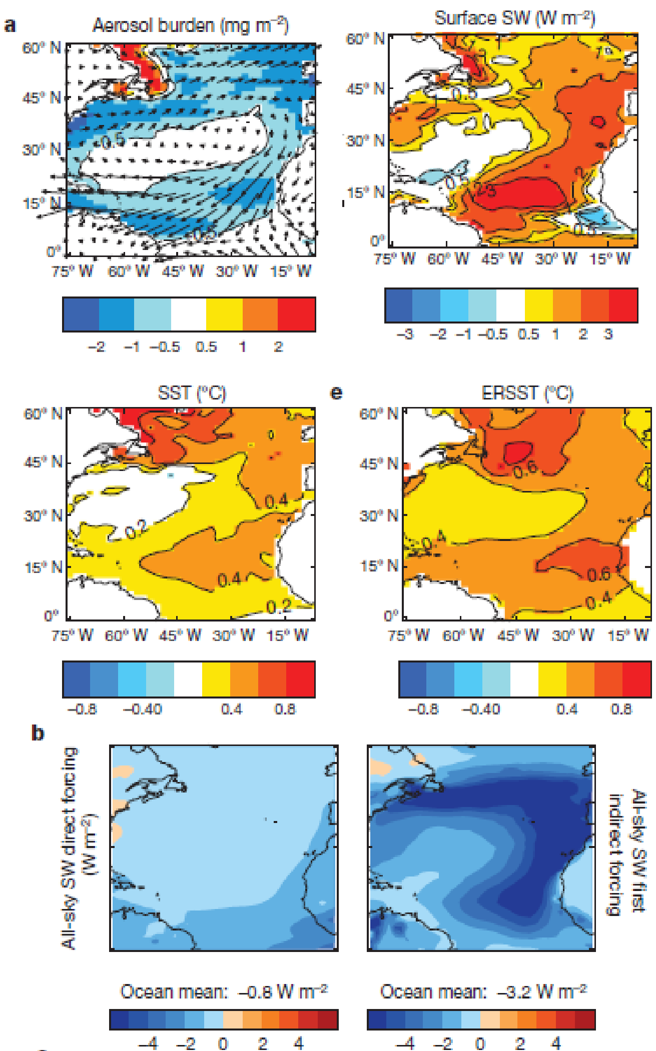


Strong response to regional forcings, sign and magnitude depend on the location of the forcing

North Atlantic multidecadal variability

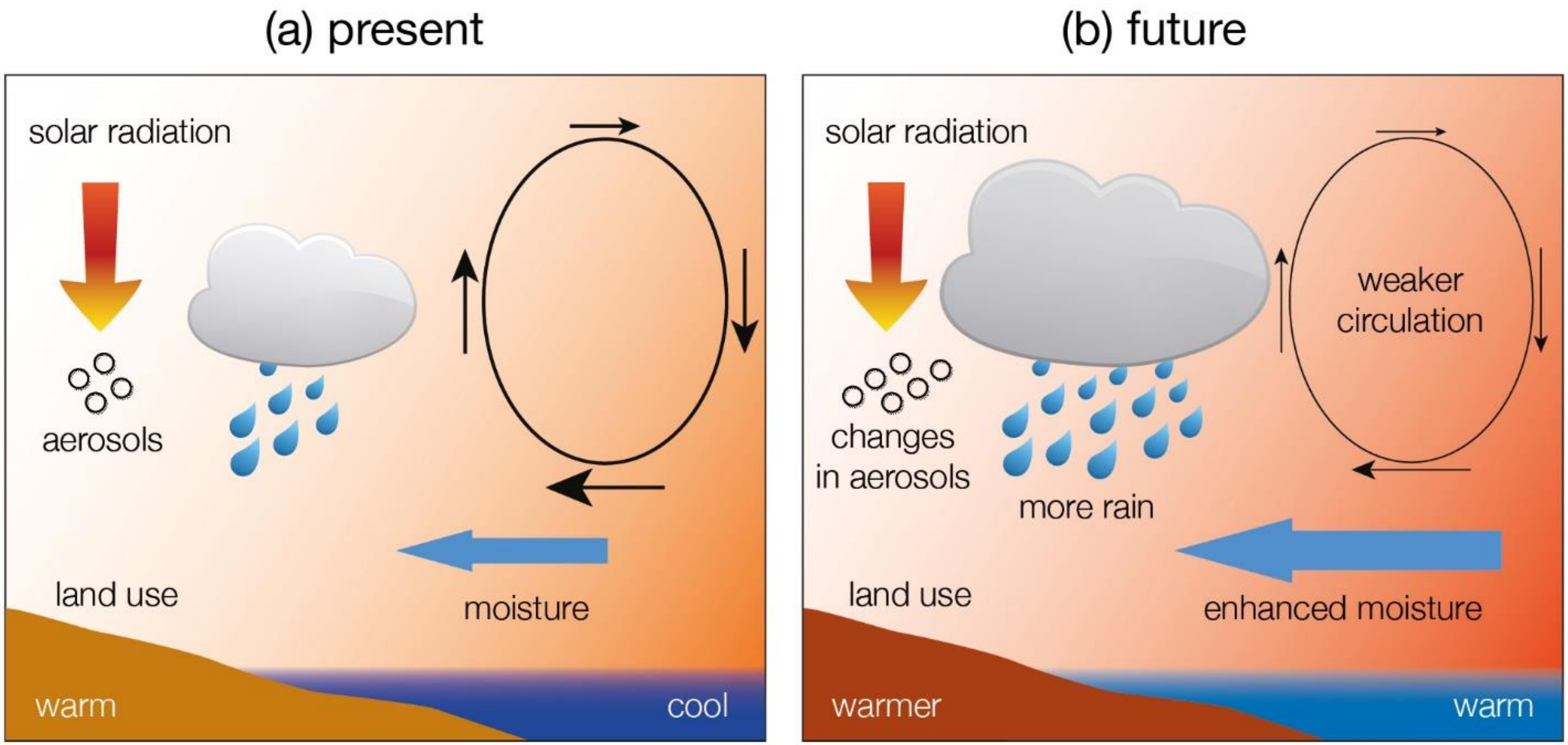
20th century changes in Atlantic sea surface temperature (Booth et al. 2012)





Aerosol emissions (indirect effects) and volcanic activity explain most of the simulated multidecadal variance in detrended 1860–2005 North Atlantic SST

Changes in the monsoon



IPCC 2013

Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle

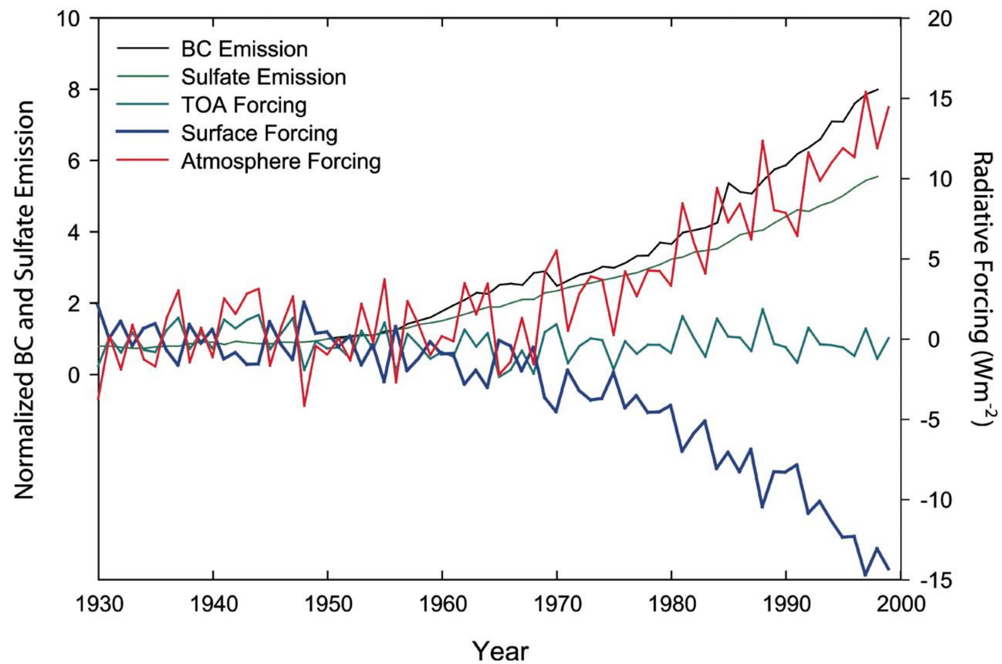
INAUGURAL ARTICLE

V. Ramanathan*†, C. Chung*, D. Kim*, T. Bettge‡, L. Buja‡, J. T. Kiehl‡, W. M. Washington‡, Q. Fu§, D. R. Sikka¶, and M. Wild||

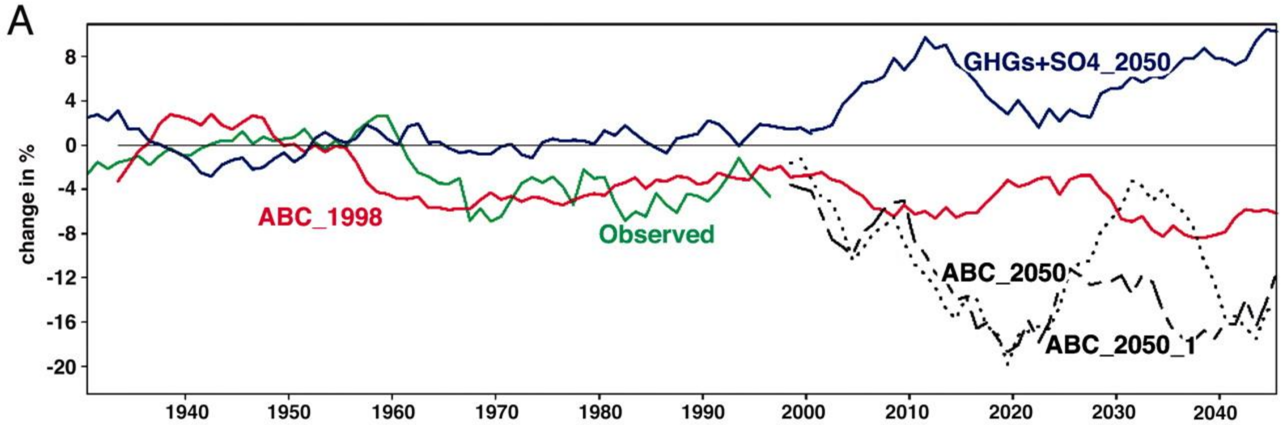
- Up to 75% of aerosol concentration over South Asia is of anthropogenic origin

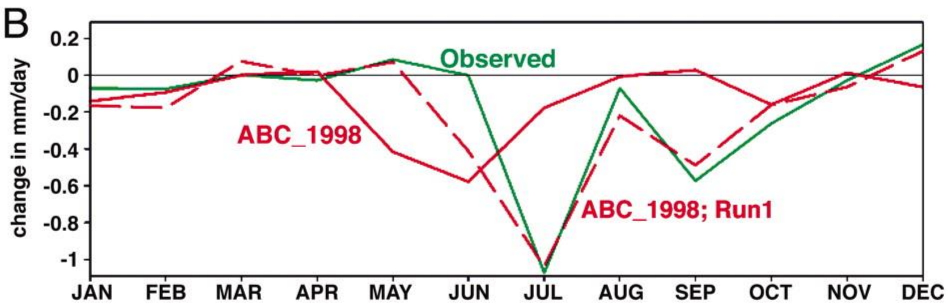
- Aerosol forcing at the surface and in the atmosphere can be an order of magnitude larger than that of anthropogenic GHGs

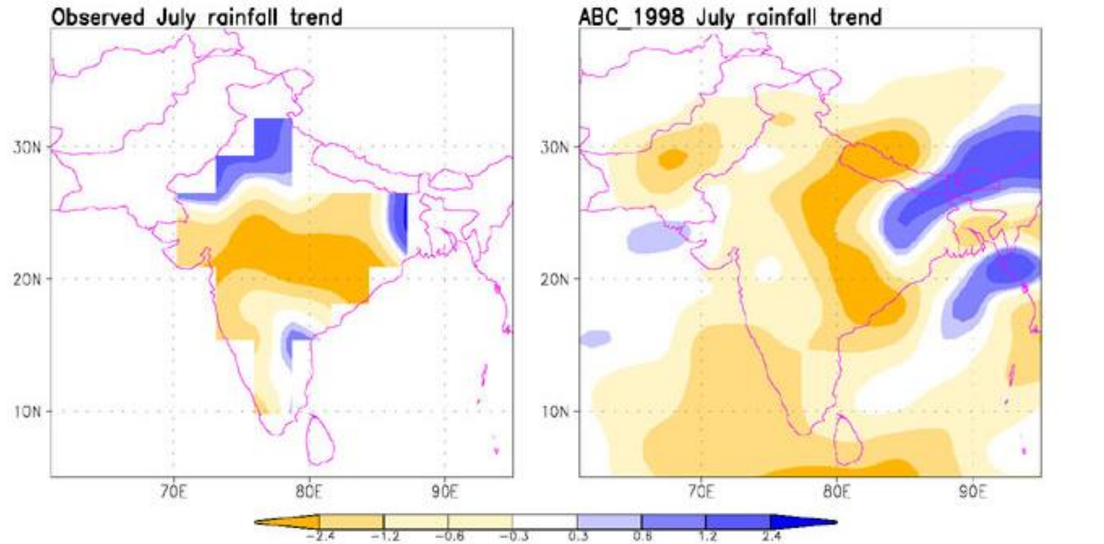
- INDOEX: a 3 km-thick brownish haze layer over most of the tropical Indian Ocean toward the Himalayas, from Southeast Asia into the western Pacific. Large content of BC (up to 14% by mass), SSA between 0.85-0.9, large perturbation to the energy budget (up to −25 Wm^{-2} in the surface mean clear-sky radiation)



Impact on precipitation

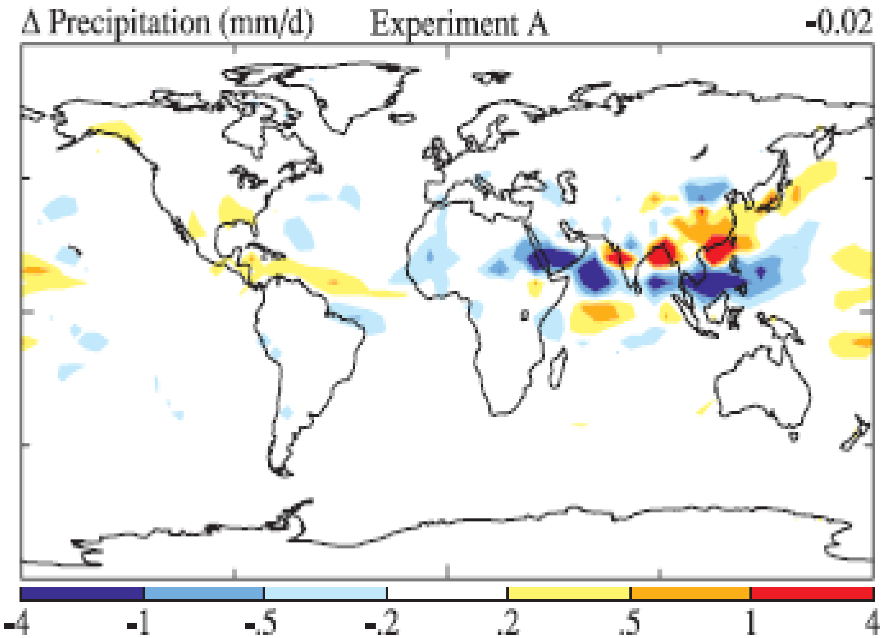


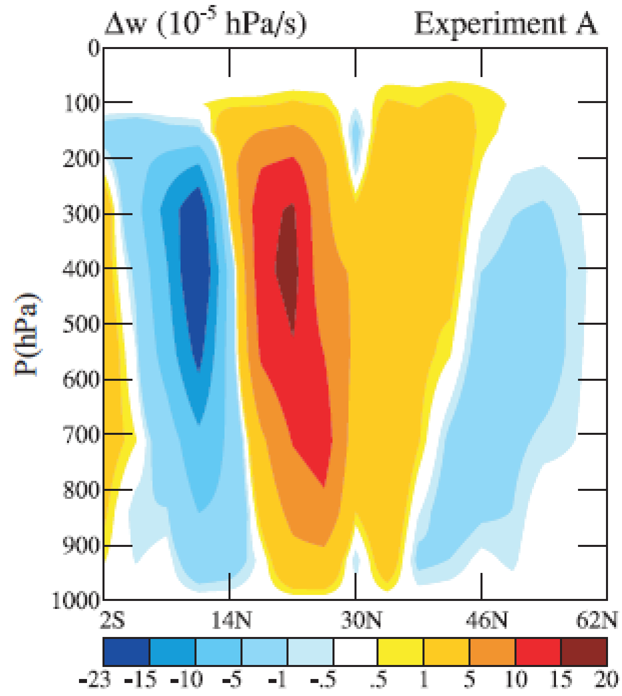




Black carbon over India and China

Changes in precipitation for 1950-1999 (Menon et al. 2002)

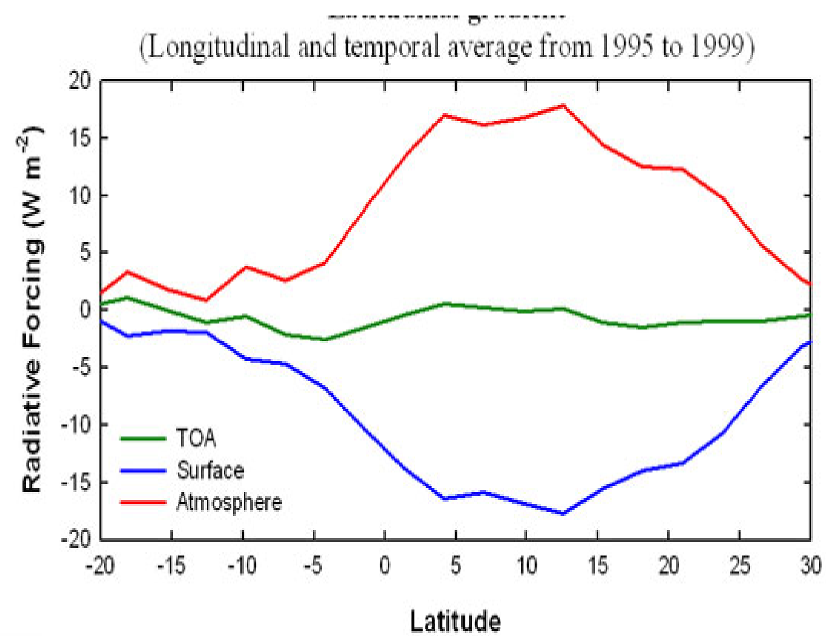


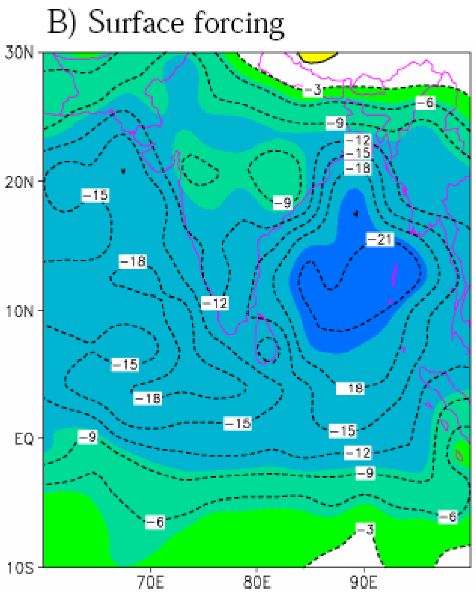


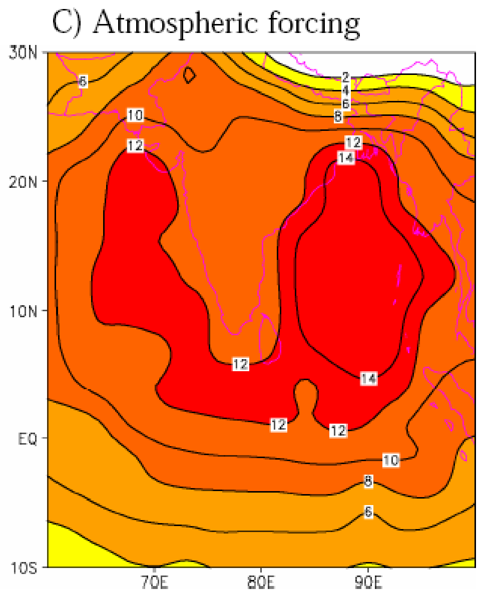
BC can induce large regional effects. South-flood north-drought precipitation pattern over China may be related to BC. Possibly Middle East

Imposed forcing and monsoon

Latitudinal gradient of radiative forcing
(Ramanathan et al., 2005)

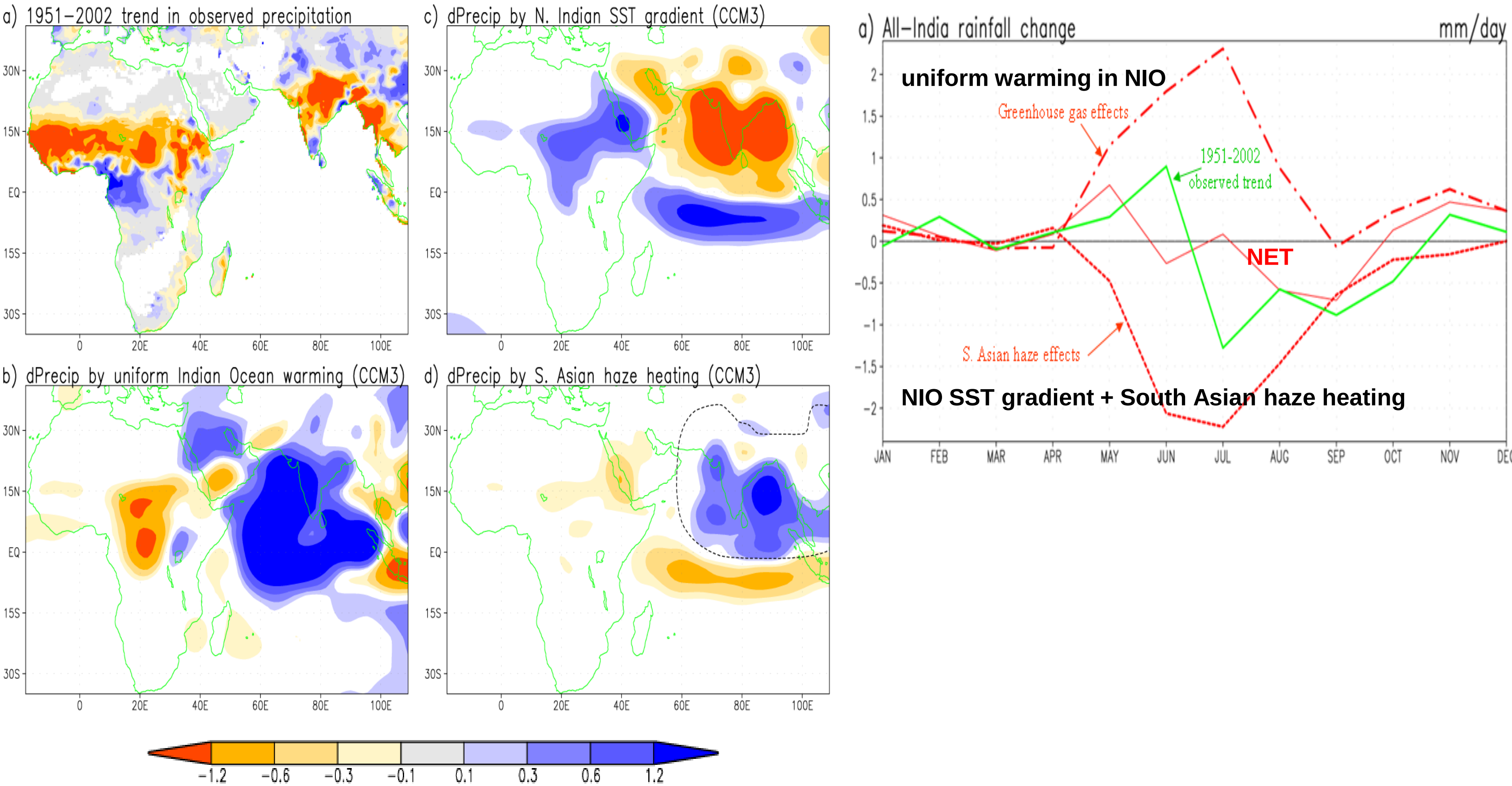






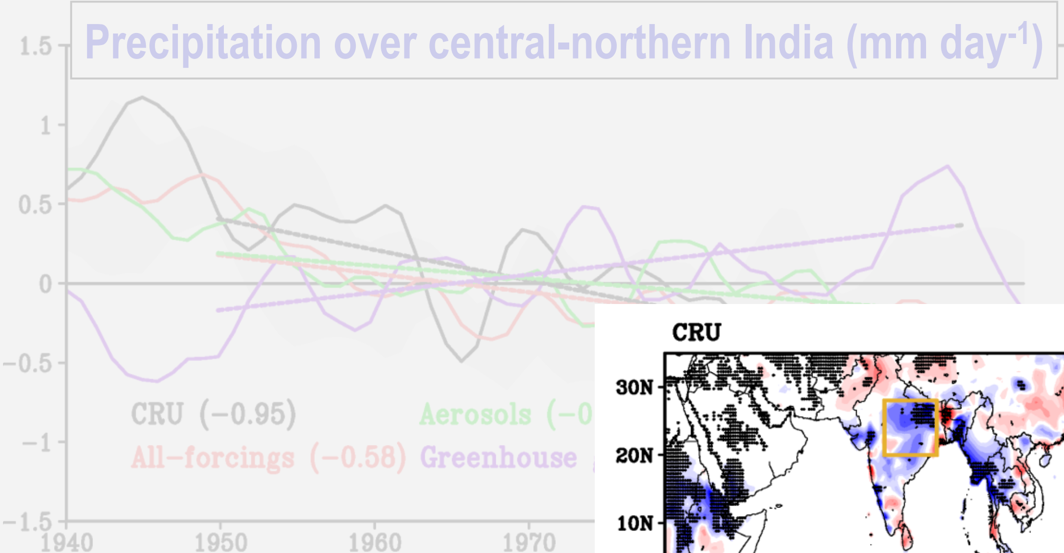
The regional distribution of the annual mean ABC forcing for 1995–1999 (B) Surface forcing. (C) Atmospheric forcing (Ramanathan et al., 2005).

SST gradient and absorption



The effect of meridional SST gradient **(c)** *more than offset the haze radiative-heating effect* **(d),** *with an* ***overall decrease*** *of monsoon rainfall over India* (Chung and Ramanathan 2006)

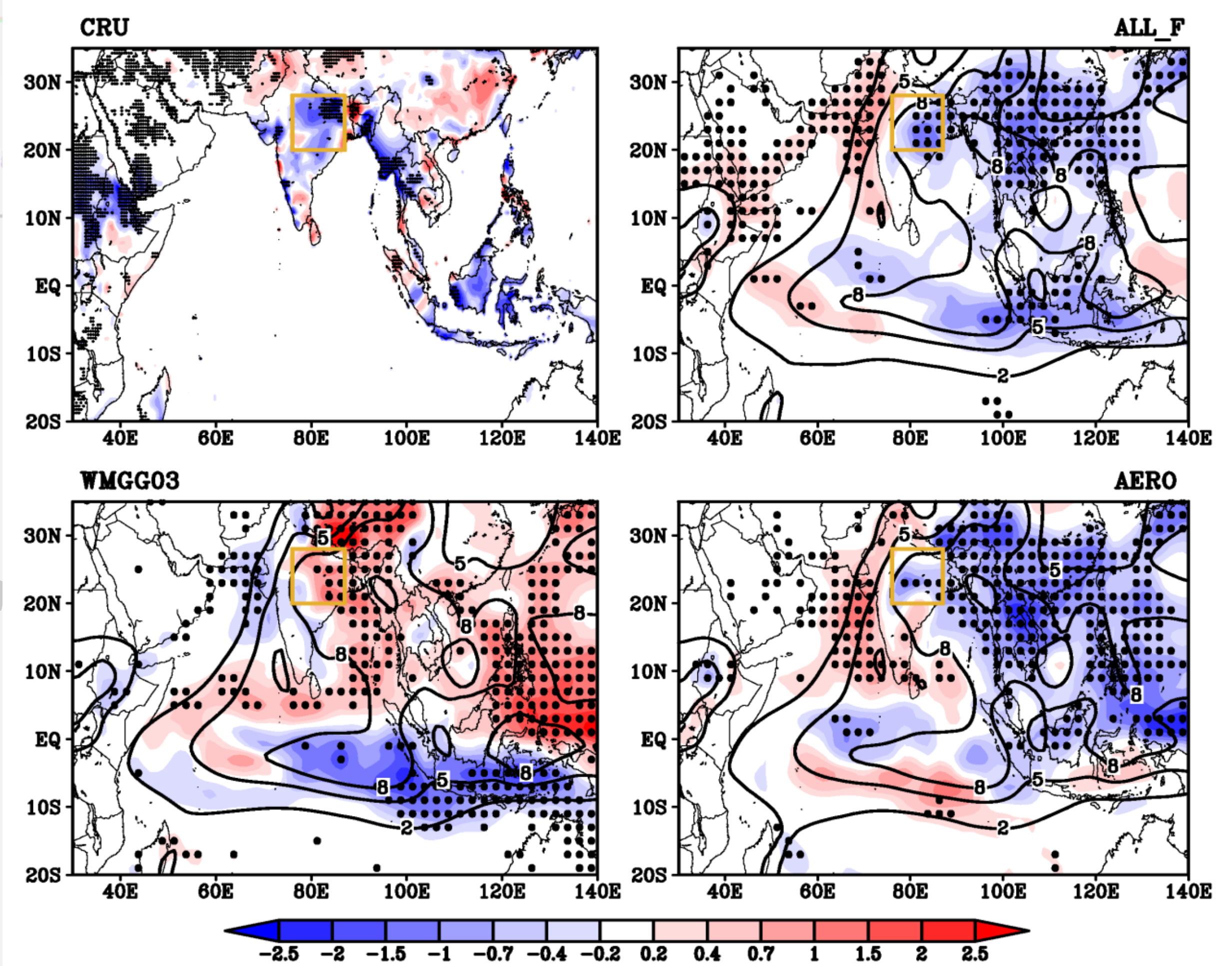
What caused the 20th century drying of the monsoon?



-9-11% over the **CN India**

-4-5% over the Country

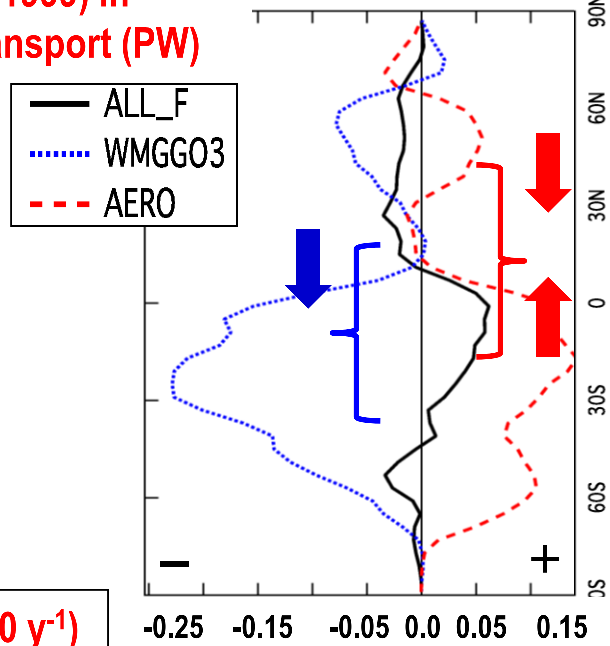
CM3 ***historical experim***



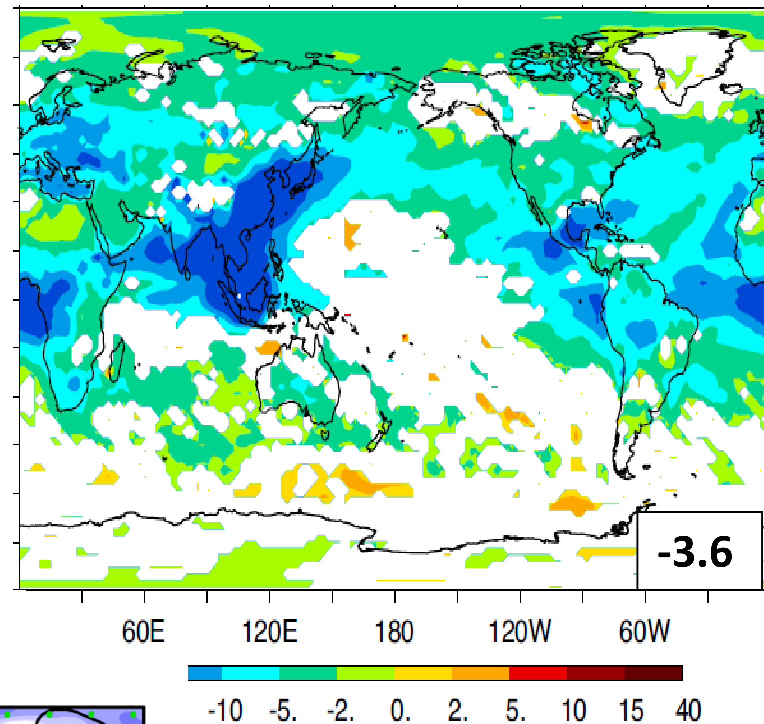
Bollasina et al. (2011)

Aerosols alter the inter-hemispheric energy balance

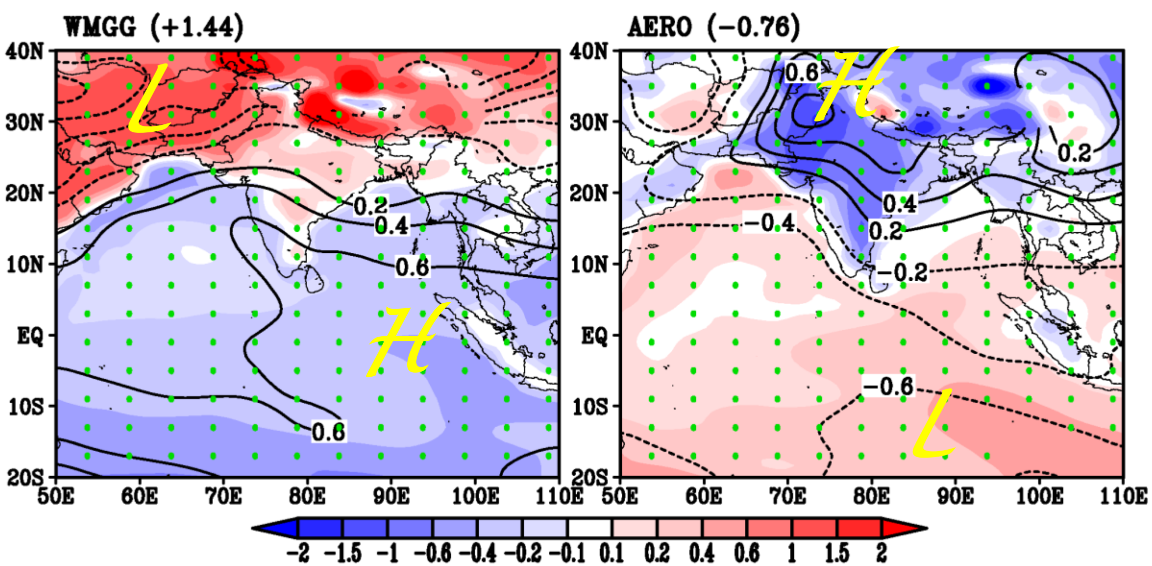
JJAS change (1950-1999) in Atmospheric Energy Transport (PW)



Sfc. RFP by Anthropogenic aerosols (W m^{-2})

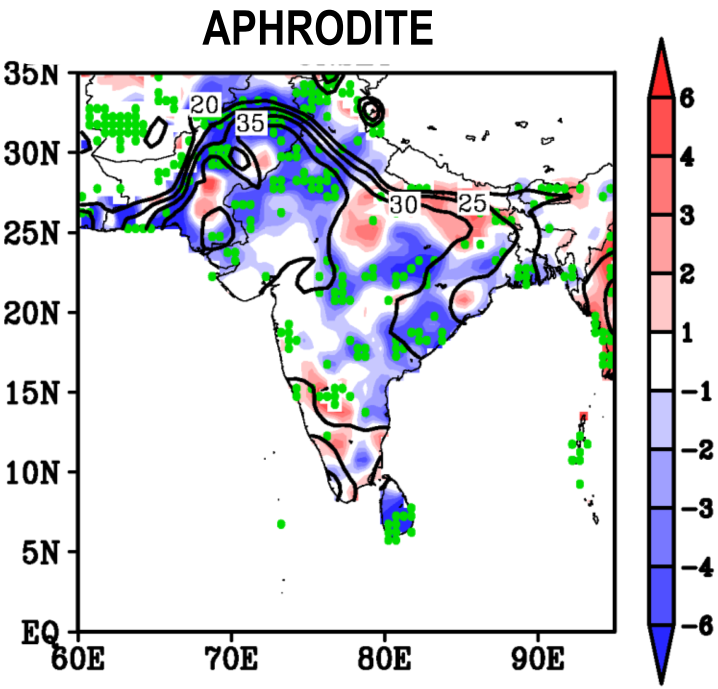


Ts (K 50 y^{-1}) & SLP (hPa 50 y^{-1})



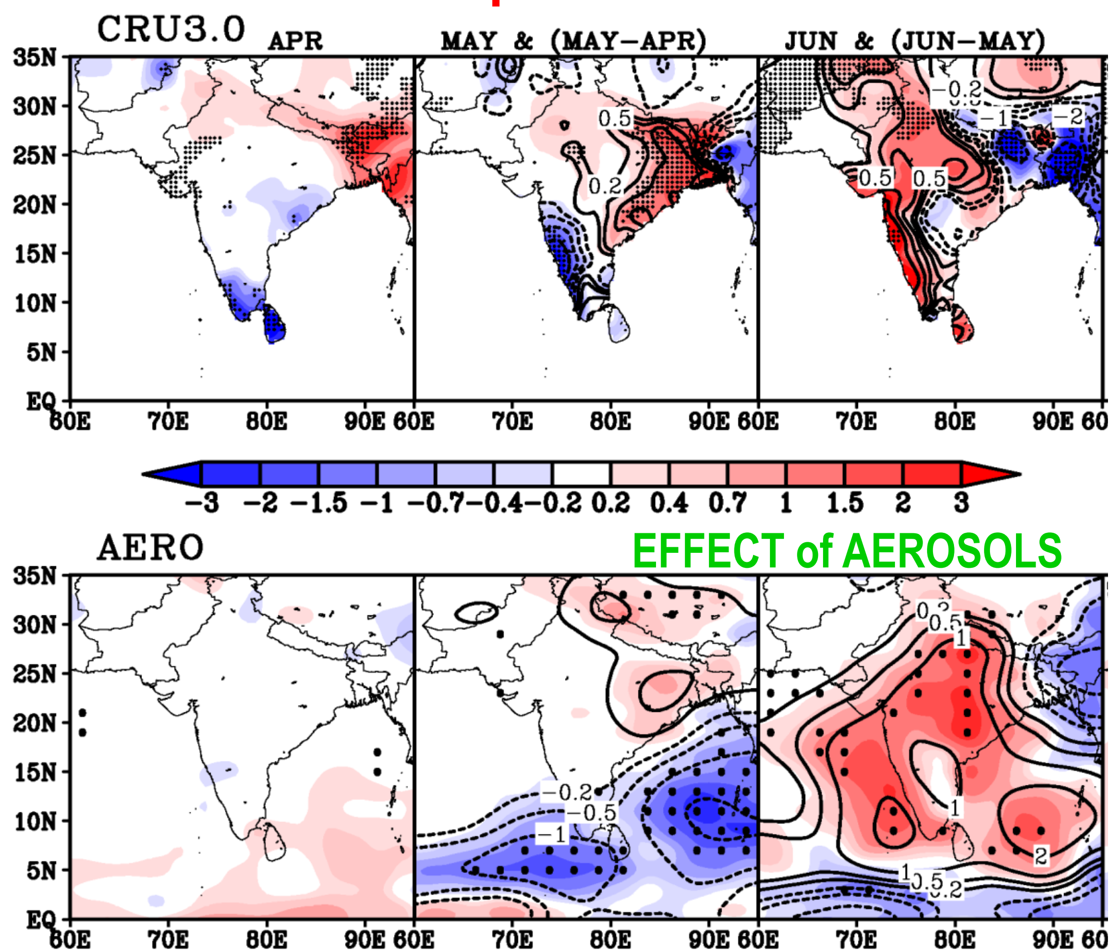
The monsoon onset has come earlier in the late 20th century

Onset change (pentads)



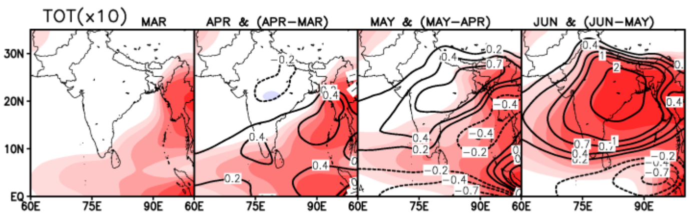
Precipitation trend

OBS

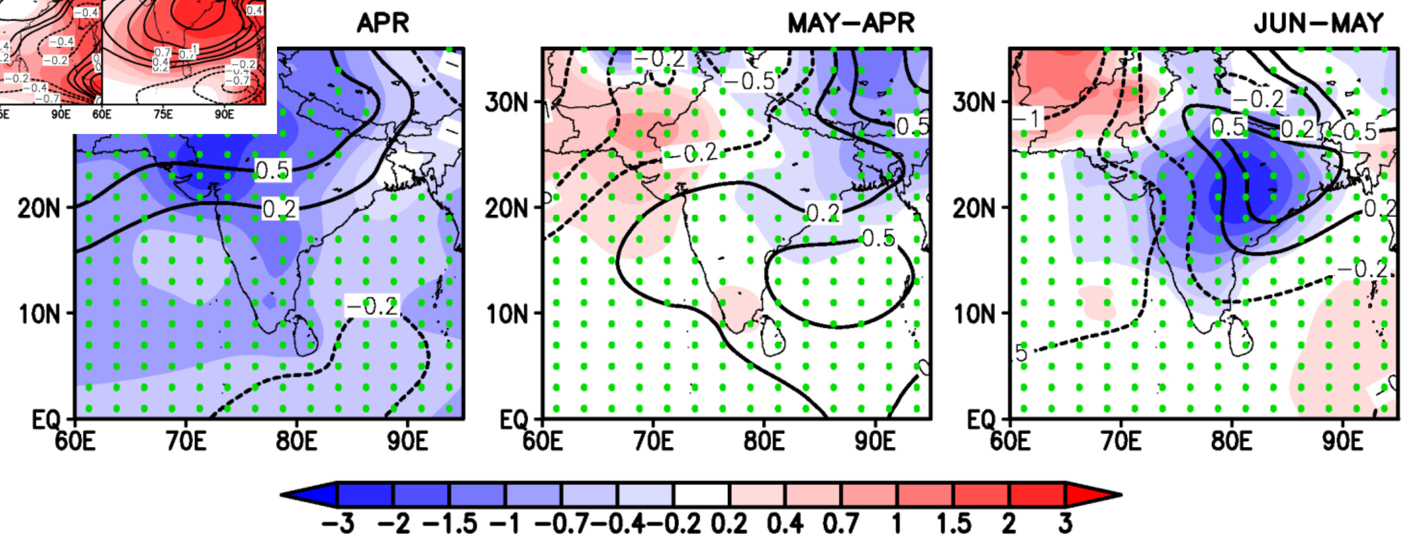


Bollasina et al. 2013c

The mechanism for the aerosol impact

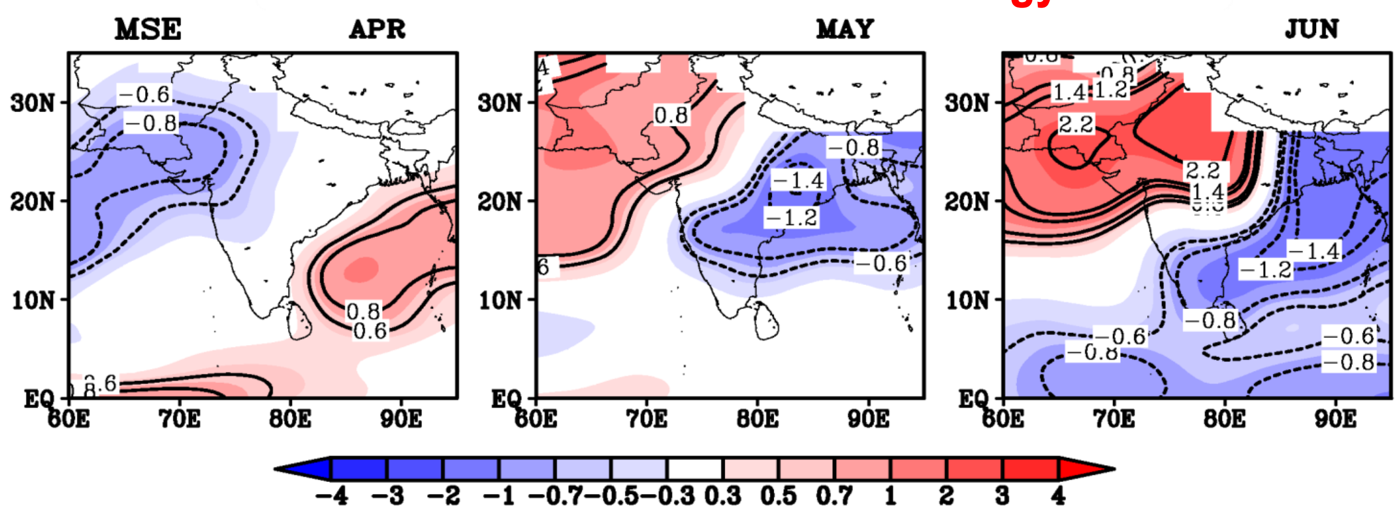


Surface Temperature and Sea Level Pressure

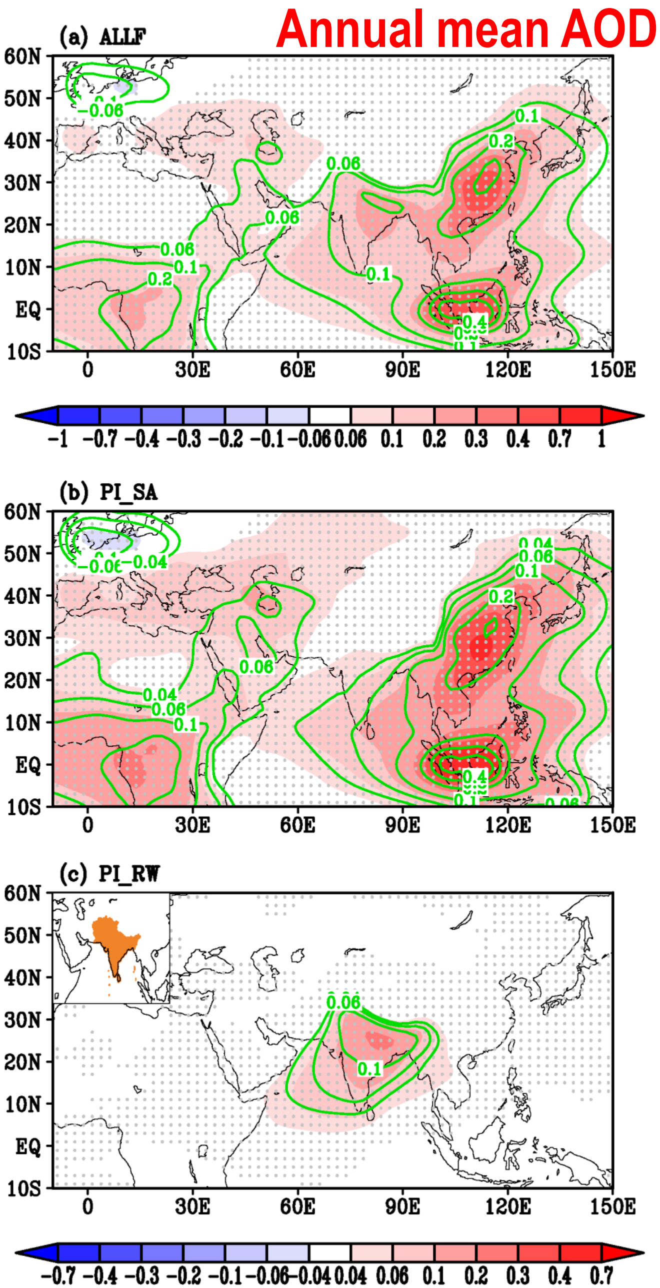


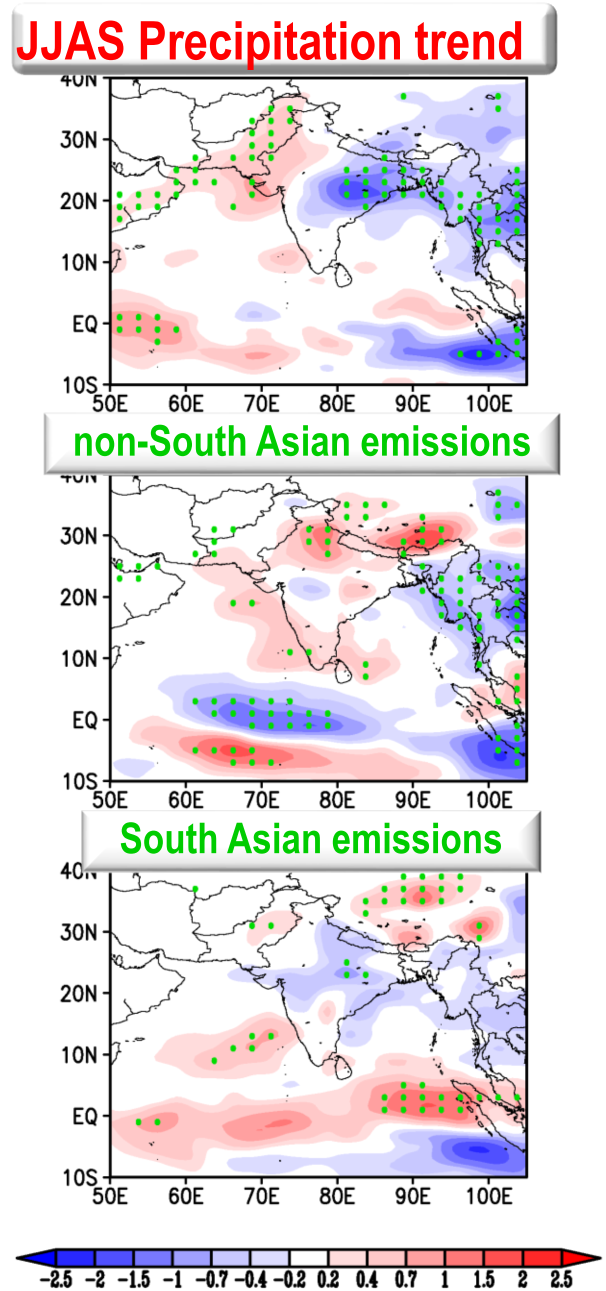
Lower tropospohe

Sub-cloud Moist Static Energy



Contrasting local and remote aerosol forcing over India





CN India

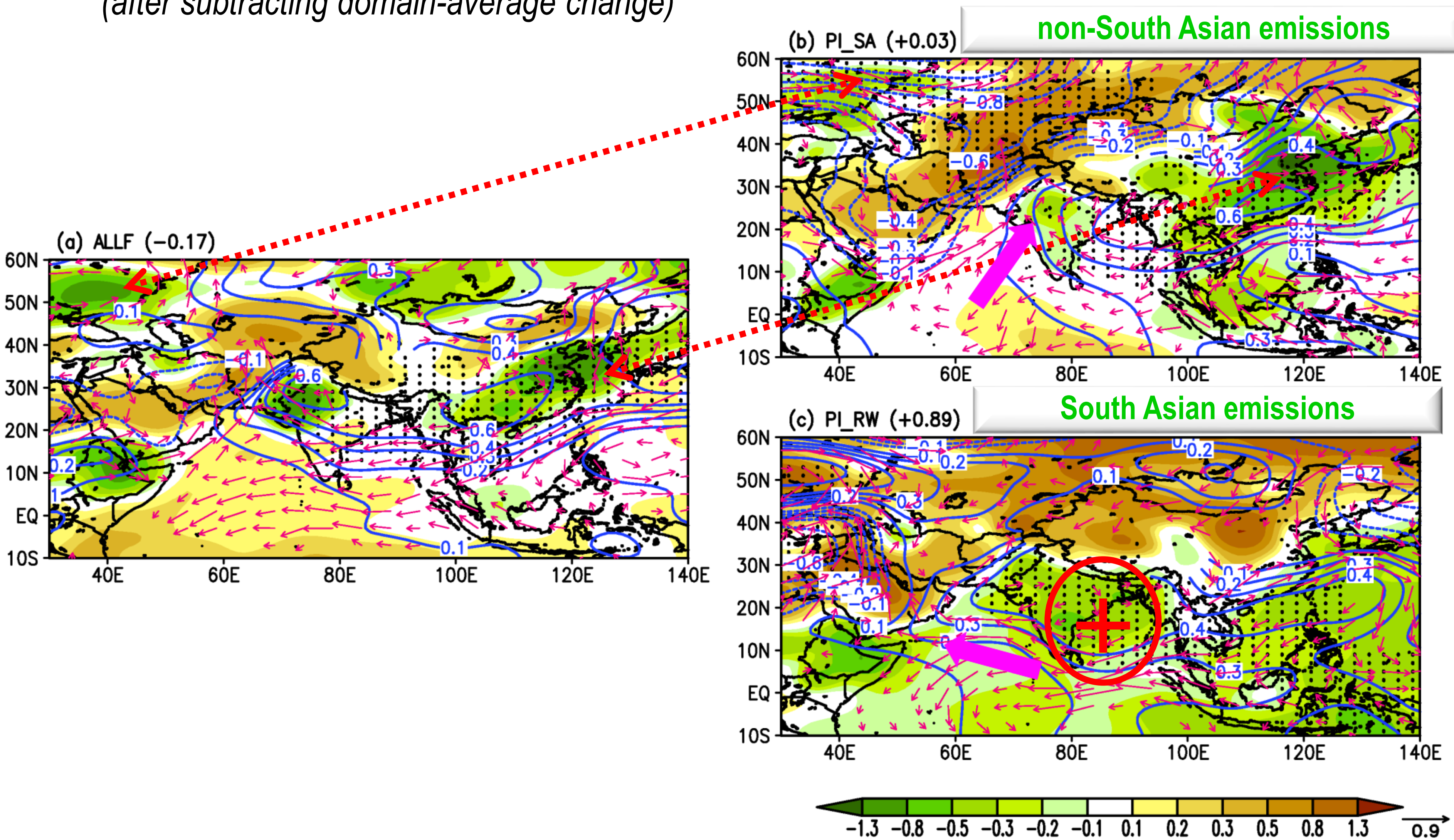
ALLF = -0.81
PI_SA = +0.24
PI_RW = -0.41

Bollasina et al. 2013d

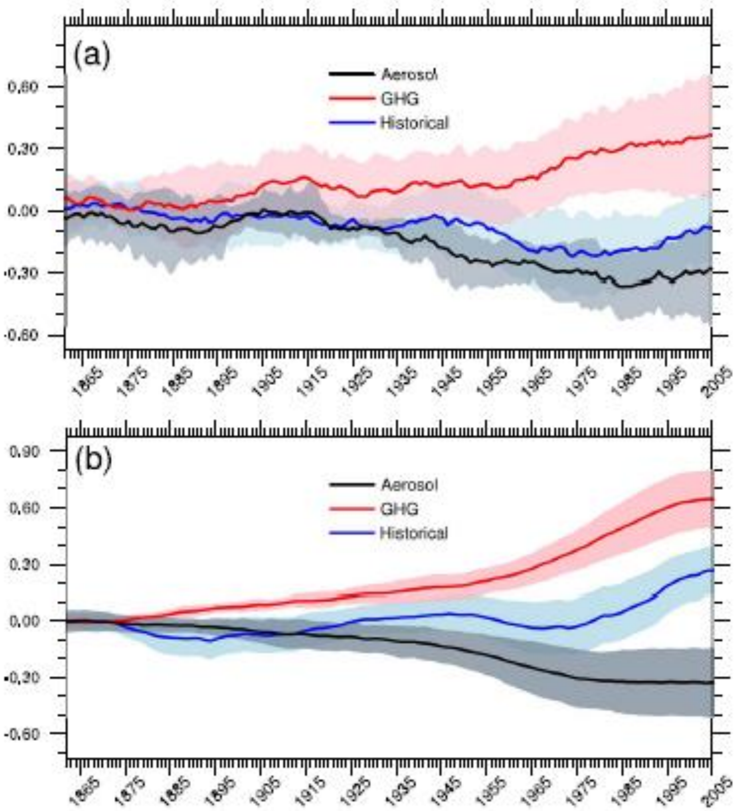
Different patterns in aerosols-induced changes at the surface

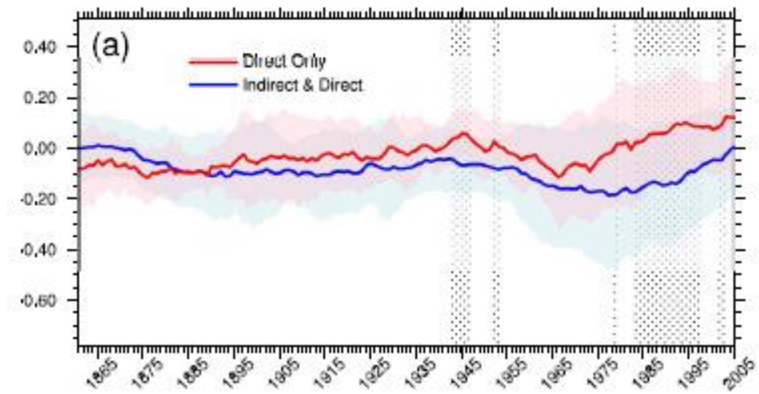
Ts (shades), SLP (contours), 850-hPa winds

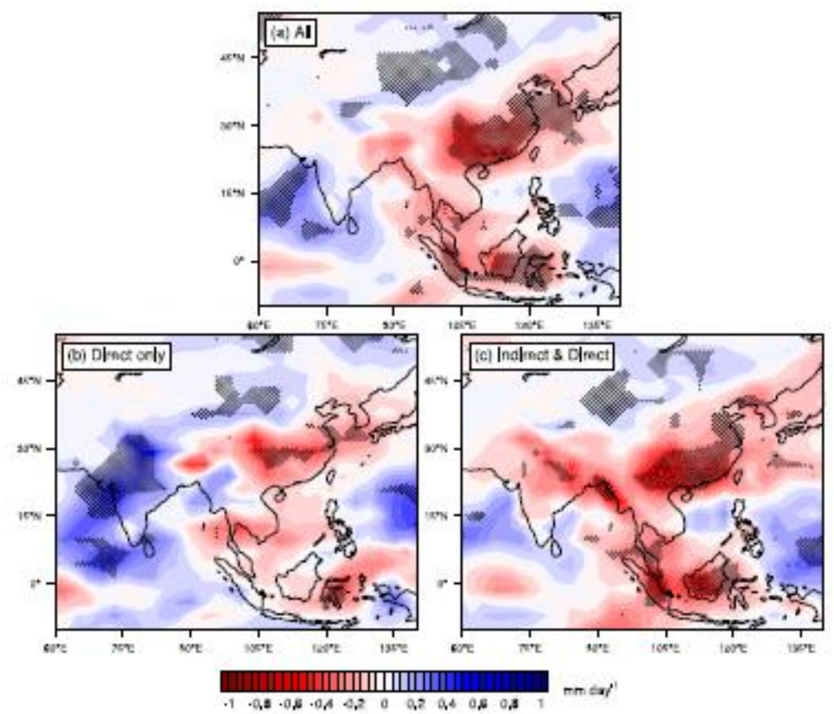
(after subtracting domain-average change)



Aerosols and 20th monsoon decline in CMIP5 models



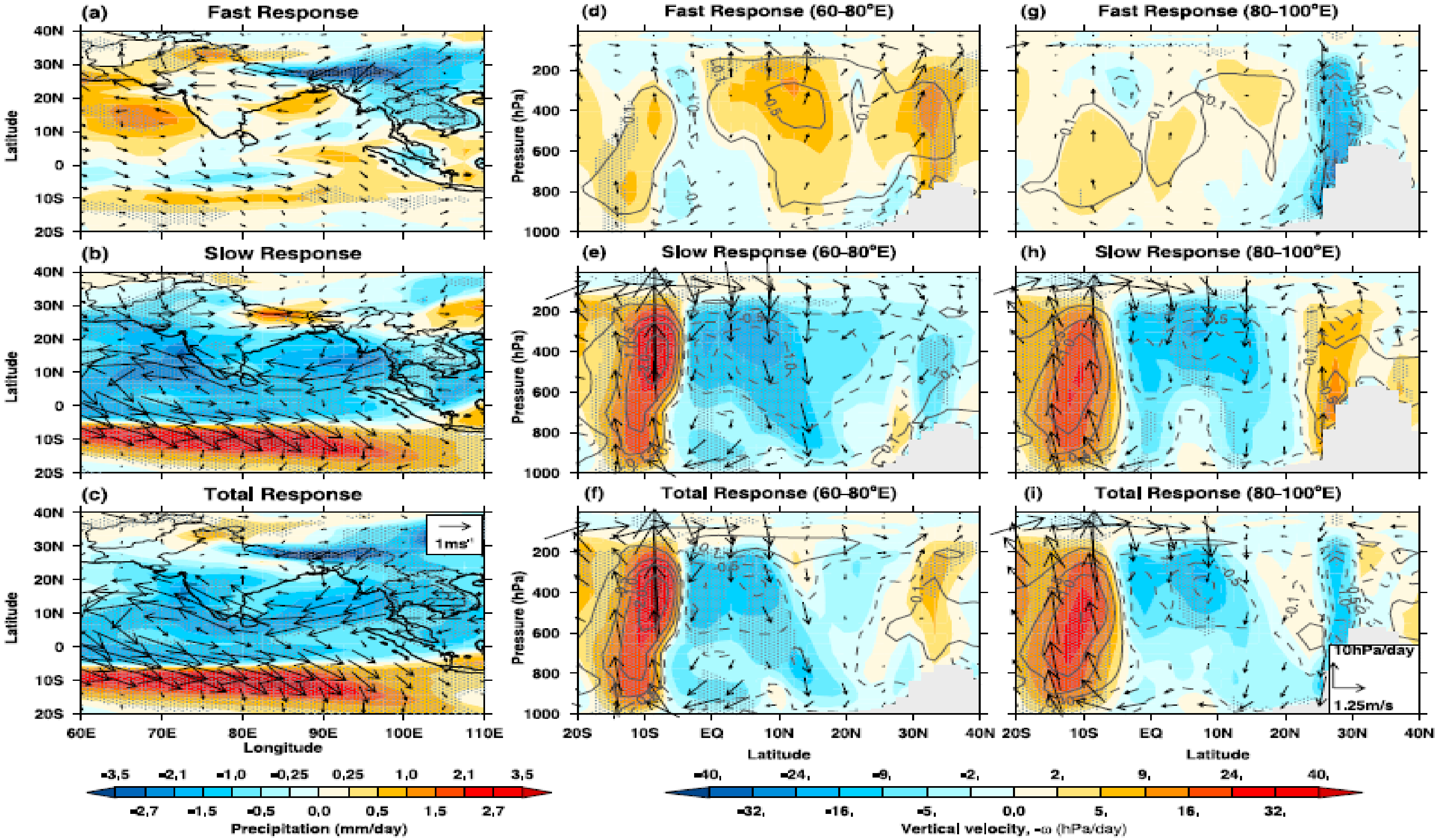




Aerosol emissions have dominated the rainfall decline
This follow the changes in the inter-hemispheric temperature gradient
Aerosol indirect effects are fundamental

Guo et al. 2015

Fast vs. slow response to aerosols



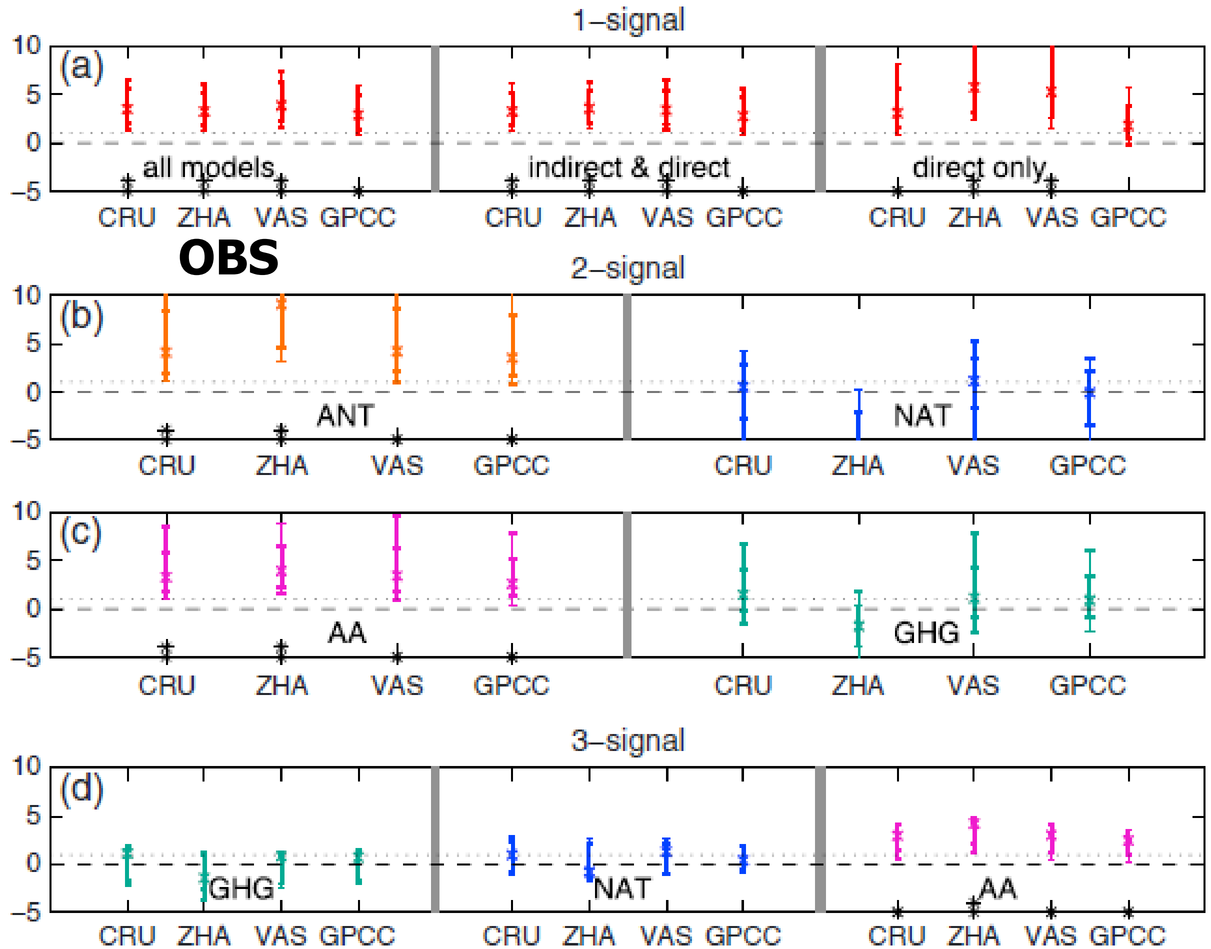
Ganguly et al. 2012

SST feedbacks prevail on rapid adjustments (radiation, clouds and land surface); inhomogeneous SST cooling reduces the meridional tropospheric temperature gradient -> slow down the local Hadley cell circulation, decreasing the northward moisture transport

The fast component dominates over land areas north of 25N and to the asymmetric response

A detectable fingerprint on the Northern Hemisphere monsoon

Detection/attribution of observed changes in NH summer monsoon 1951-2005 (Polson et al. 2014)

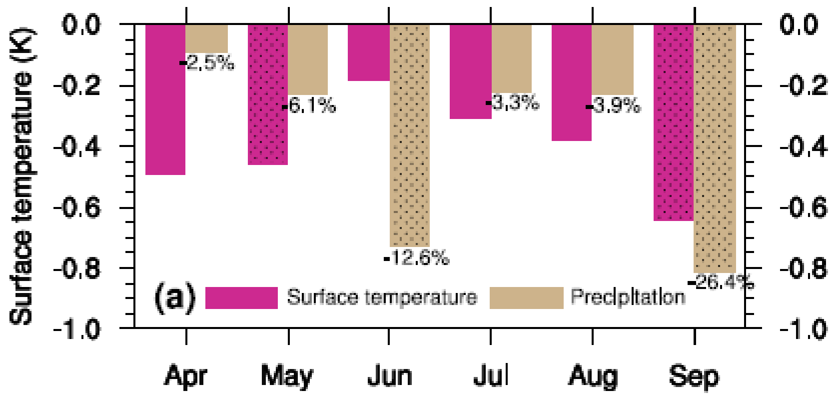


The observed changes can only be explained when including the influence of anthropogenic aerosols, even after accounting for internal climate variability

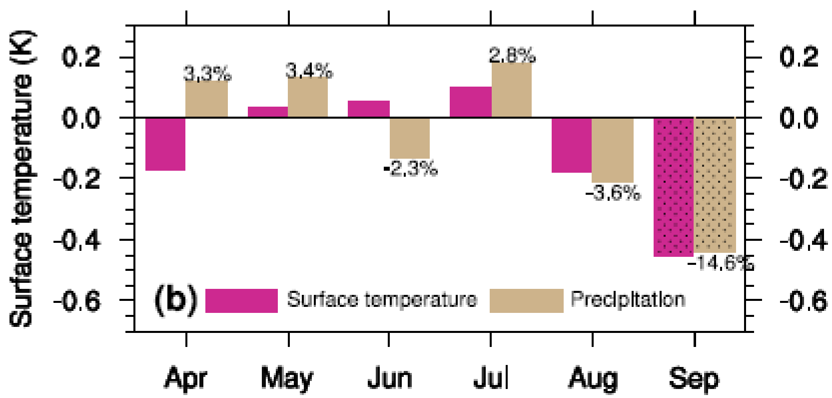
East Asia aerosols

Temperature and precipitation changes due to EA sulfates and BC (Guo et al. 2013)

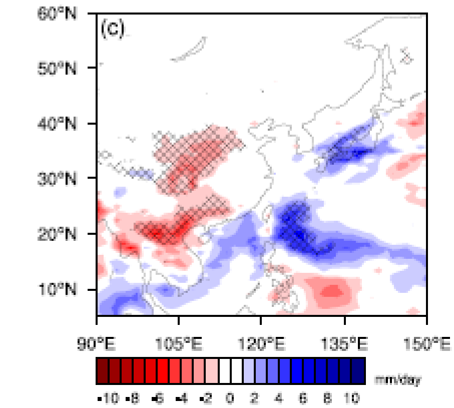
Sulfates

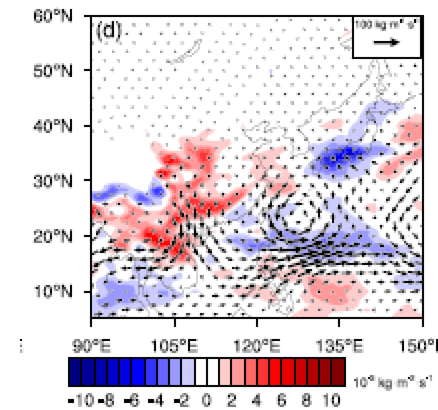


BC



P and moisture flux

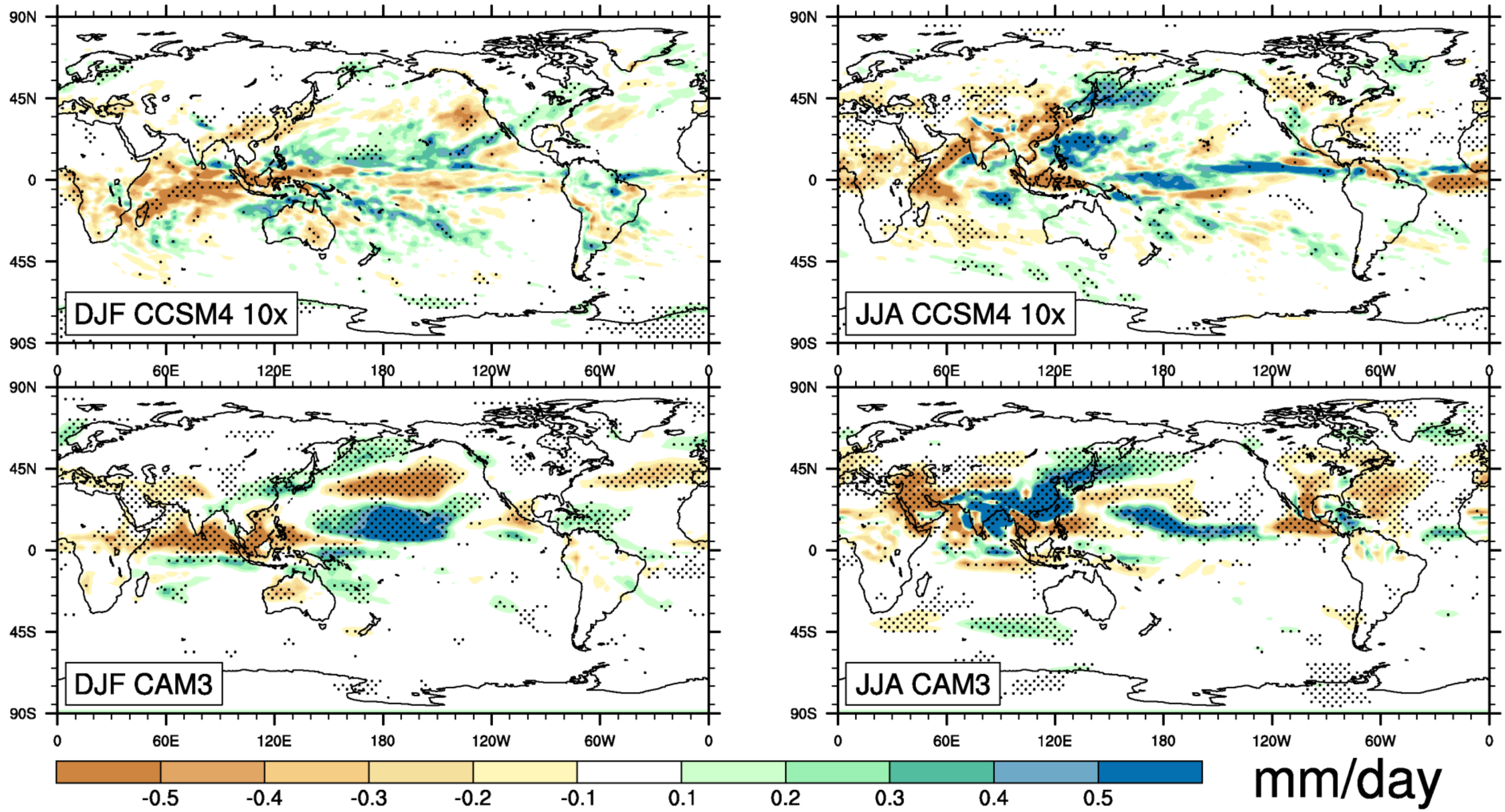




Impact of aerosols are more significant in the withdrawal phase. Land-sea contrast and reduced moisture fluxes

Remote impact from Asian aerosols

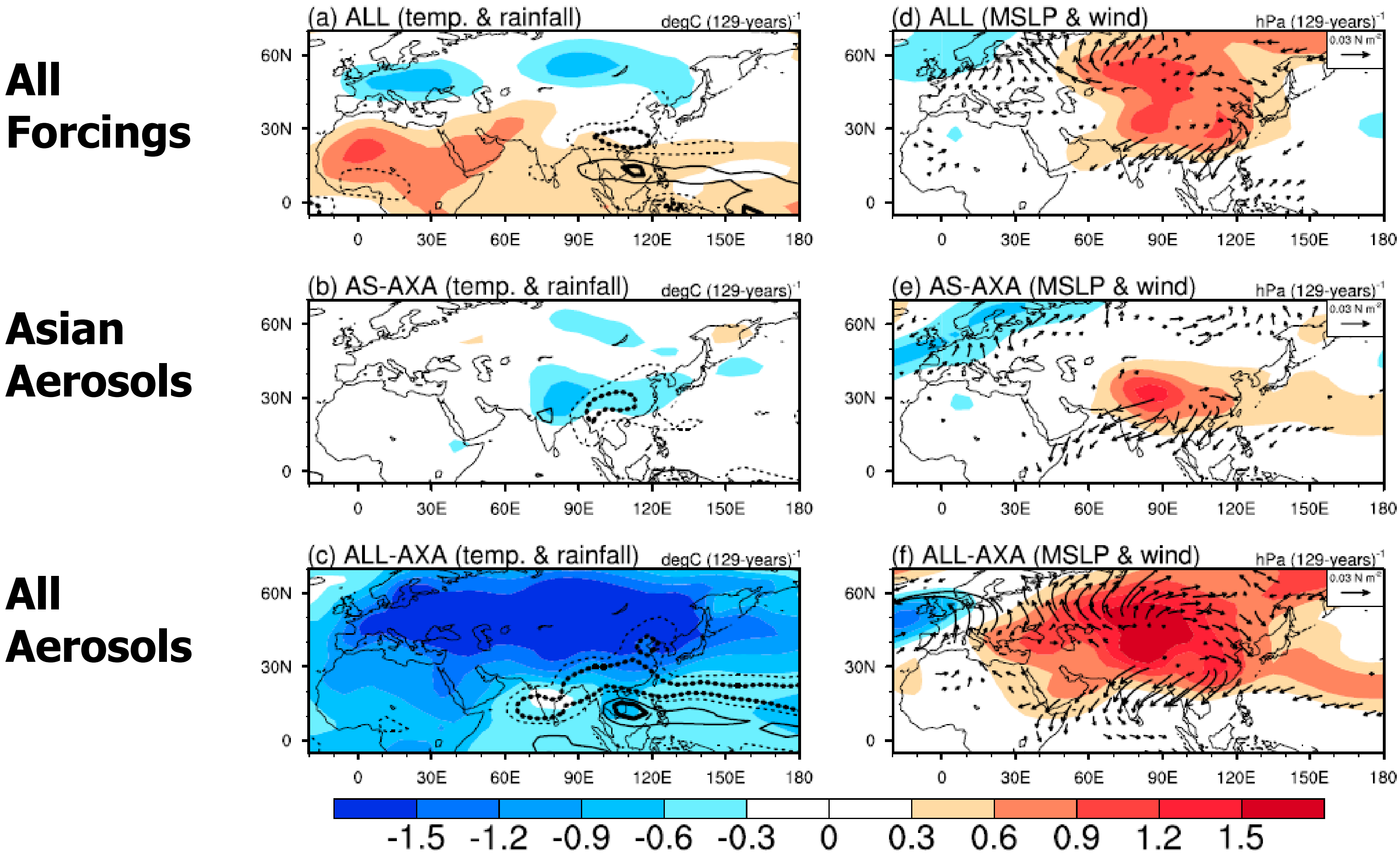
Future changes in precipitation due to Asian BC aerosols (Teng et al. 2012)



Aerosol cooling slows the hydrological cycle over most of the US, with accelerated southerly moisture flux toward the south central areas

Contribution of remote aerosols on Asia

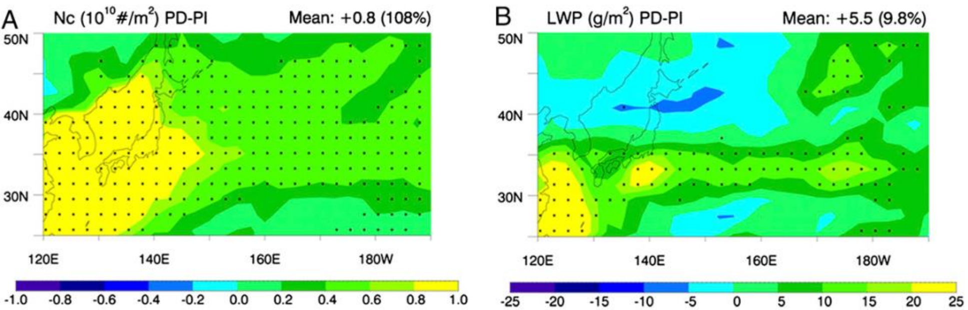
Boreal summer trends 1871-1999 (Cowan and Cai, 2011)

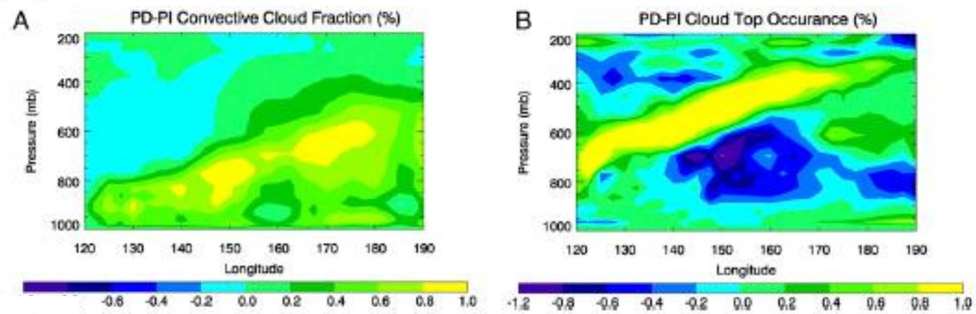


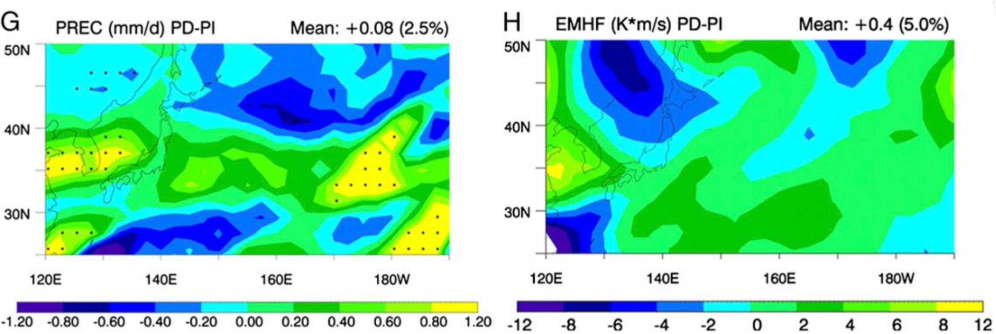
All forcing patterns in the monsoon are reproduced only accounting for the impact of aerosols from non-Asian sources

Pacific storm tracks

Changes due to long-range transport of anthropogenic aerosols across the north Pacific (Wang et al. 2014)

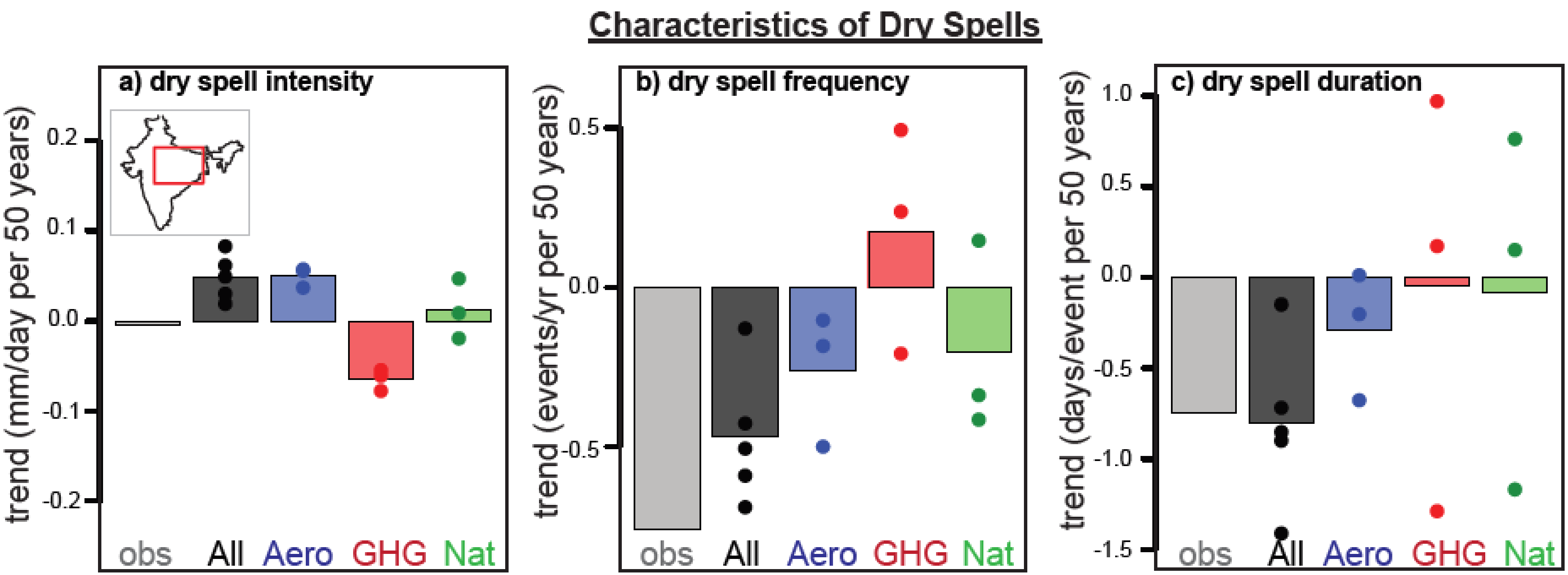






Long-range transport of Asian pollution induces convective invigoration by aerosol-cloud interactions, increased precipitation and poleward heat transport

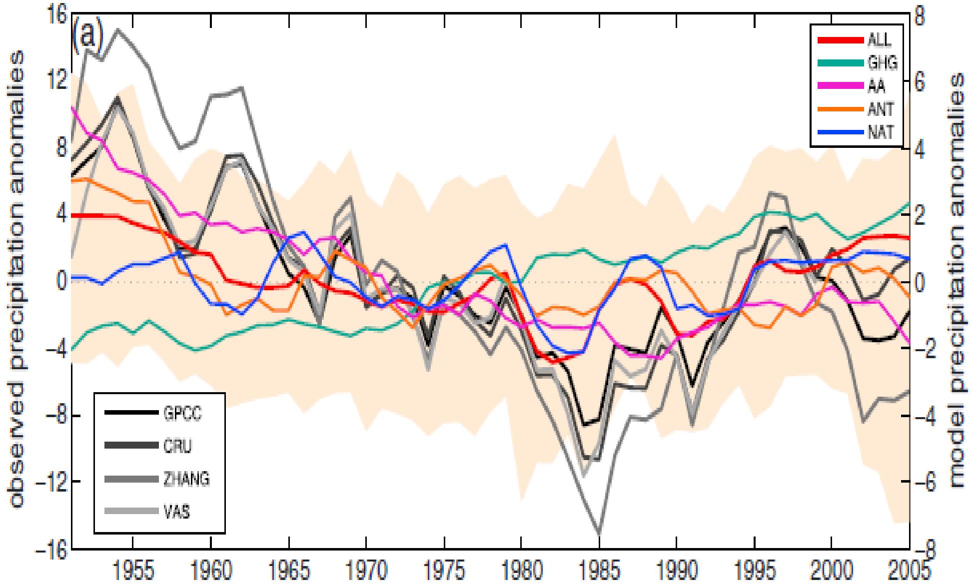
A possible impact on Indian monsoon daily variability



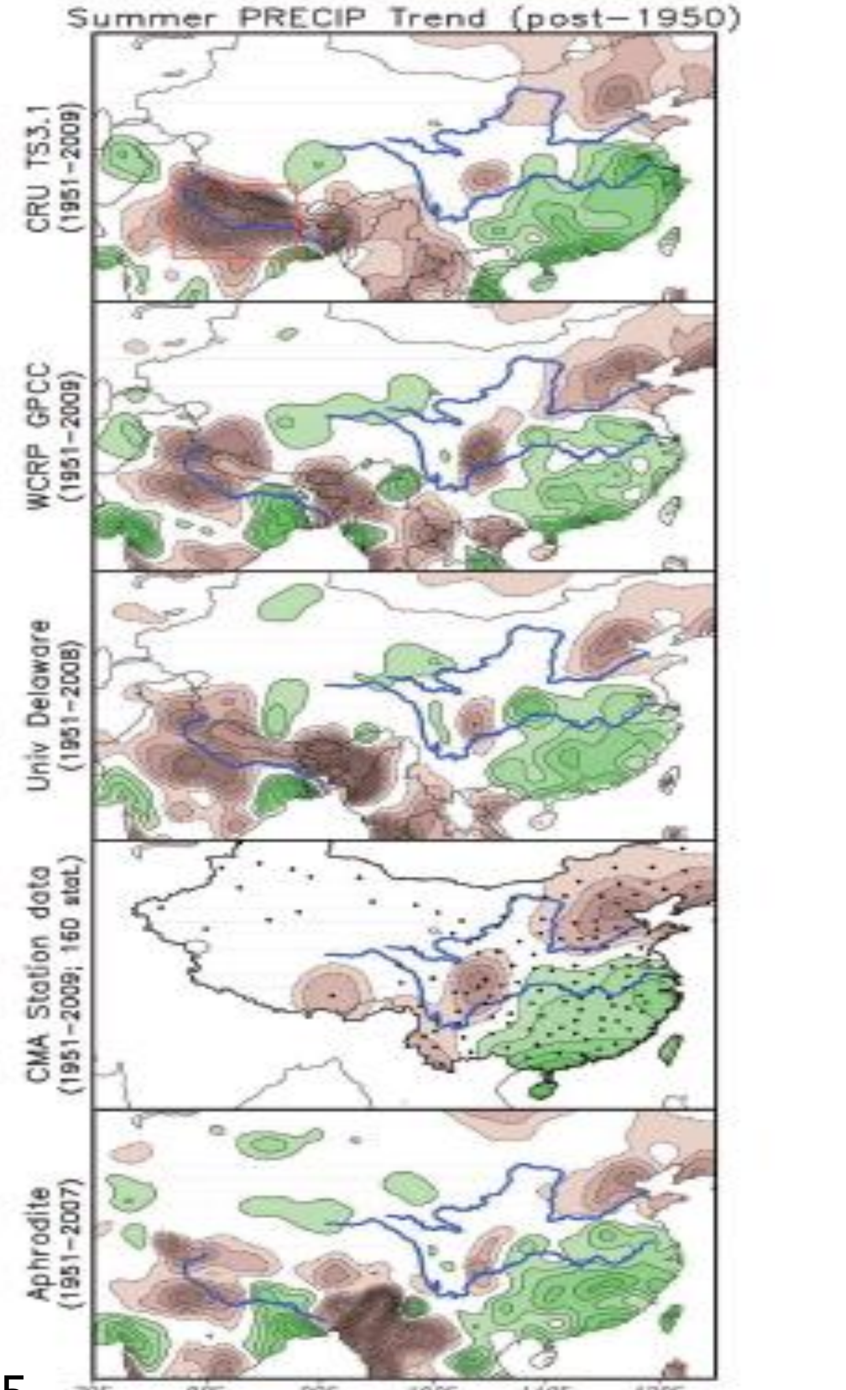
Singh, Bollasina, et al., 2016

Should we blindly trust observations?

An example: monsoon long-term changes



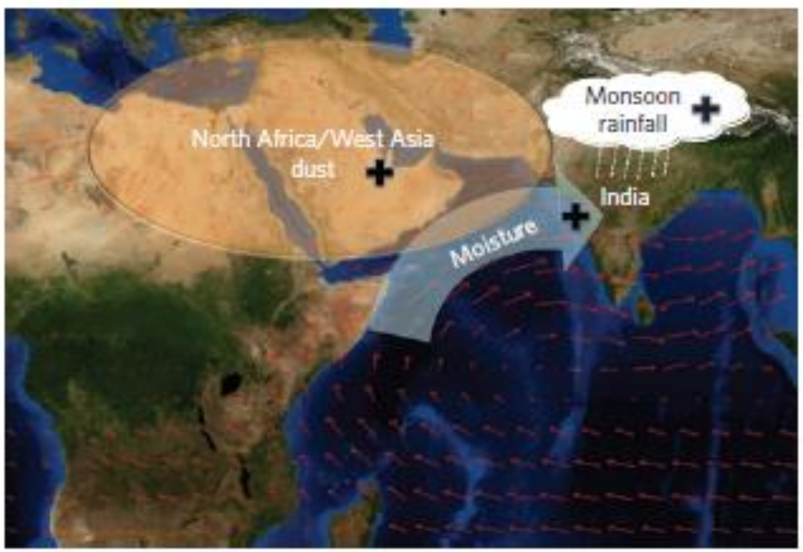
Polson et al. 2014

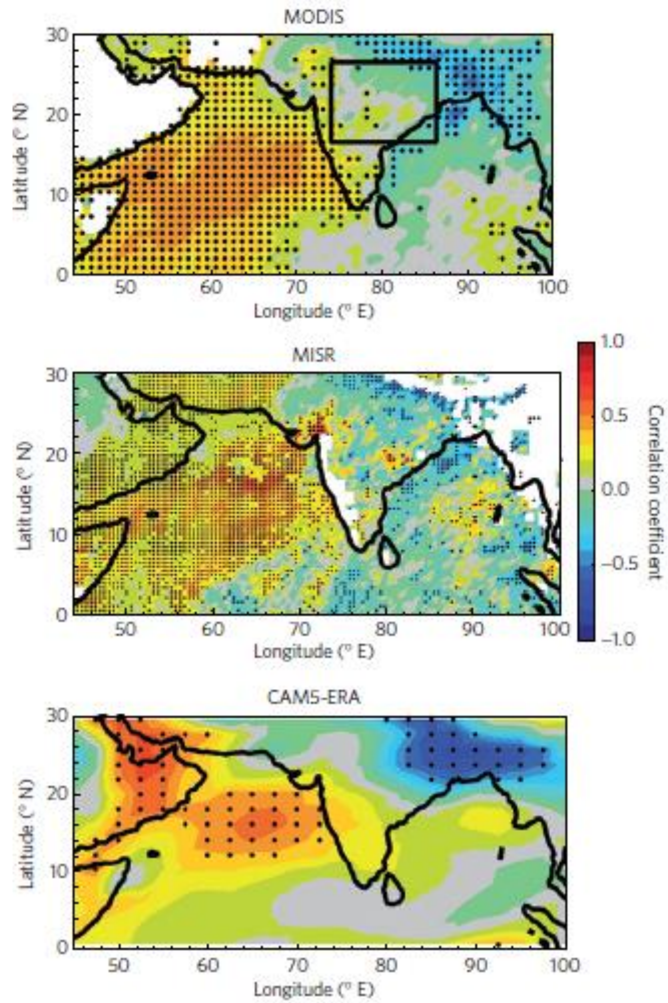


Nigam et al. 2015

Natural aerosols are also important!

Short-term modulation of Indian summer monsoon rainfall by West Asian dust





Vinoj et al. 2014

Back to where we started …

- Key for predicting and projecting future climate change at larger scale
- Progress has been made in the last decade
- Low confidence in regional climate variability and change in monsoon regions
- Many uncertainties (aerosols, models, knowledge, many spatial/time scales)
- Need for a coordinated **process-based** effort

Key Issues

- Observations (Poor coverage and limited data)
- Scale dependency (Spatial and temporal, e.g., interannual vs. decadal, spatial heterogeneity in patterns of change)
- Characteristics (e.g., extremes vs. seasonal)
- Timing (e.g., seasonal cycle - onset vs. withdrawal)
- Upstream/downstream effects (remote effects/teleconnections)
- Simulation is challenging (overall large biases, incremental improvement in CMIP5; mean state vs. changes?)
- Forcing uncertainties (On top of GHG: Aerosols? Natural variability? Linearity? Land use?)