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Radiative Forcing Overview

- non-Kyoto gases

PHIL RASCH

PNNL Atmospheric and Global Change Division

Richland, WA

With thanks to K. Caldeira,
S. Ghan, C Hannay, D. Jacob, B. Kravitz,
R. Neale, A. Robock, B Santer,

Climate Forcing

- A measure of the net change in the energy balance of the Earth system in response to some external perturbation.
  - (Watts per square meter)
  - quantifies the energy imbalance that occurs when the external change takes place
  - *Does not measure the system response*
- Forcing Agent: An atmospheric trace constituent that has an effect on the energy balance of the Earth.
  - (Aerosols, Ozone, others)

The Medium is the message… (Marshall McLuhan)

- A medium affects the society in which it plays a role not only by the content delivered over the medium, but also by the characteristics of the medium itself

The Forcing is the message… (Phil Rasch)

- A “forcing agent” affects the society in which it plays a role not only by the energy delivered (or not) via a “forcing agent”, but also by the characteristics of the “forcing agent” itself

Setting the stage

- What is my goal?
  - To try to compare/connect emissions/forcings of non-GHG forcing (aerosols, ozone, others) to GHGs
  - Identify some of the ways that they affect climate, and society of relevance to IAMs

- Take home messages
  - GHGs are long lived -> well mixed -> forcing is homogenous
    - Emissions = Burdens = Forcing = Impacts
  - Shorter lived species with lifetimes of days to weeks have global *and local impacts* that are likely to matter to IAMs
    - The shorter lifetime changes the way the forcer impacts climate
    - May make it important for IAMs to treat the impacts on "precipitation", "health", "agricultural productivity", "energy production" with more granularity than you are used to doing.

Climate System Energy Balance

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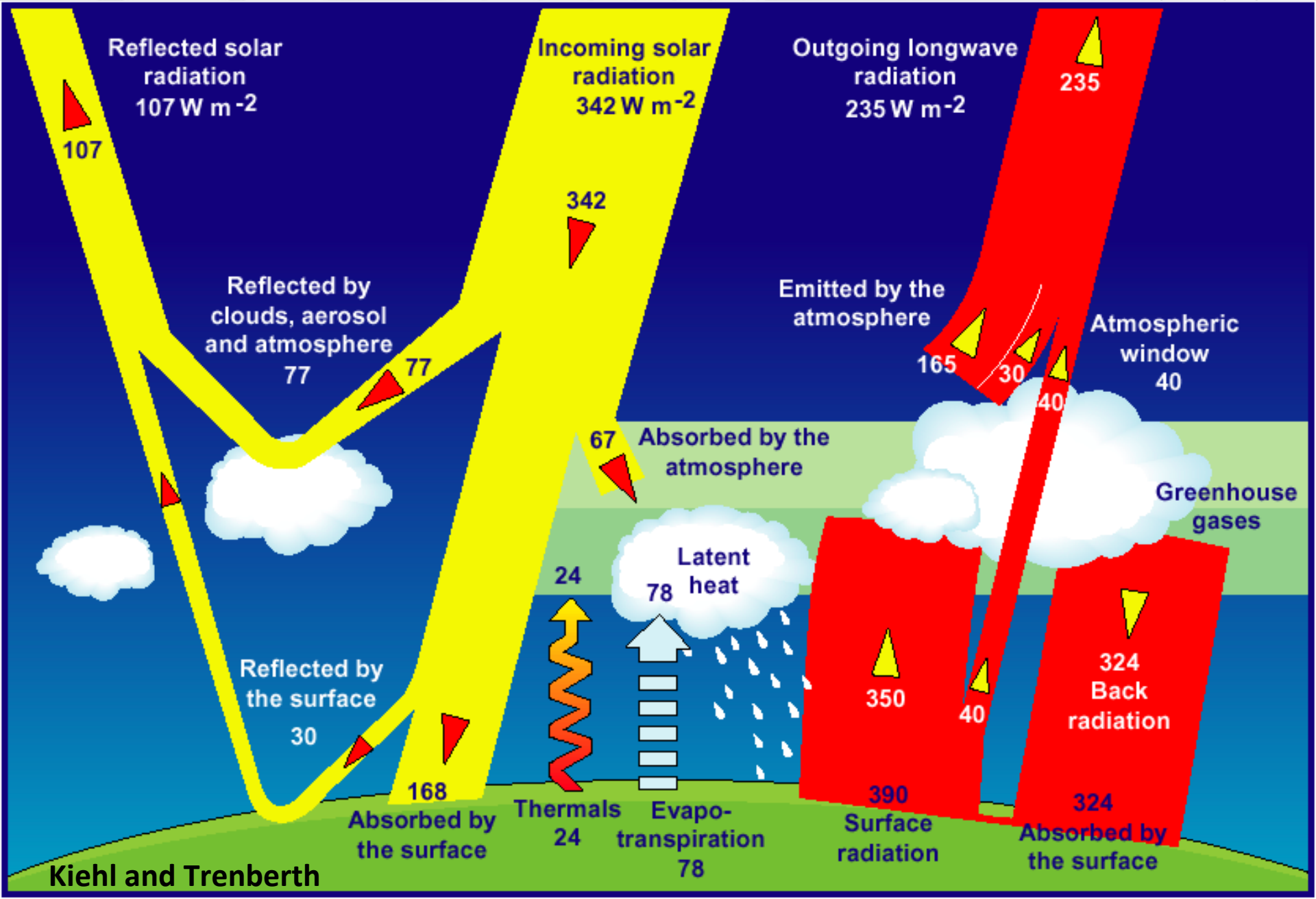

Nature:
600-1,500 megatons CO_2 per year

Humanity:
28,000 megatons CO_2 per year

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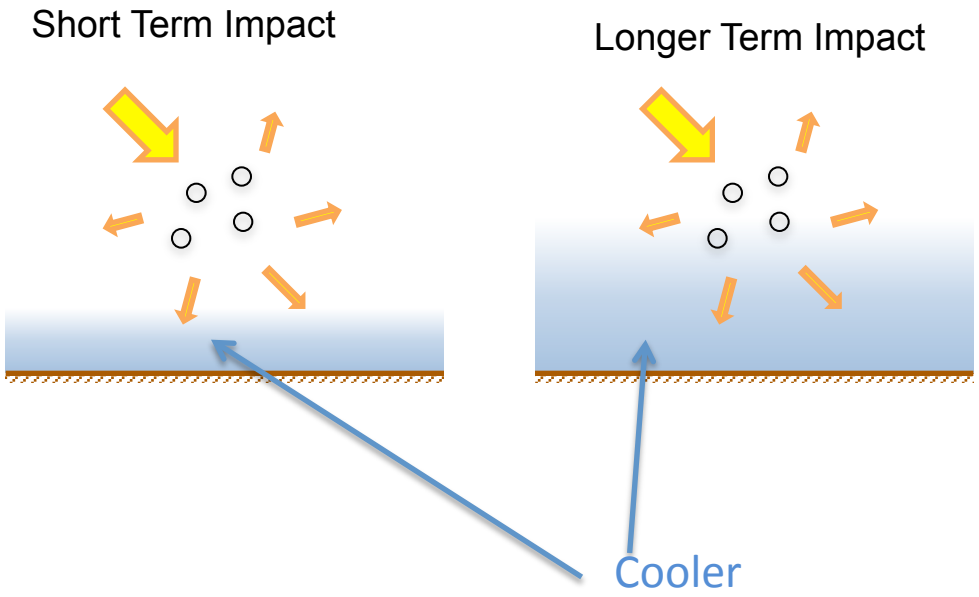
30 ×

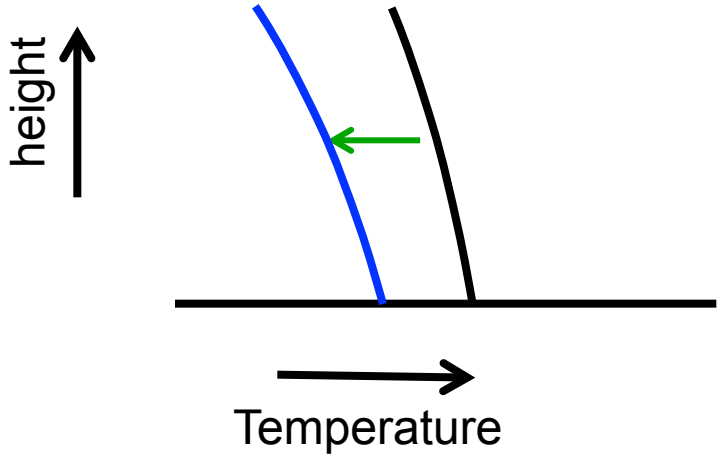
NASA, Jay

www.polarfoundation.org/www_sciencepoles/pics

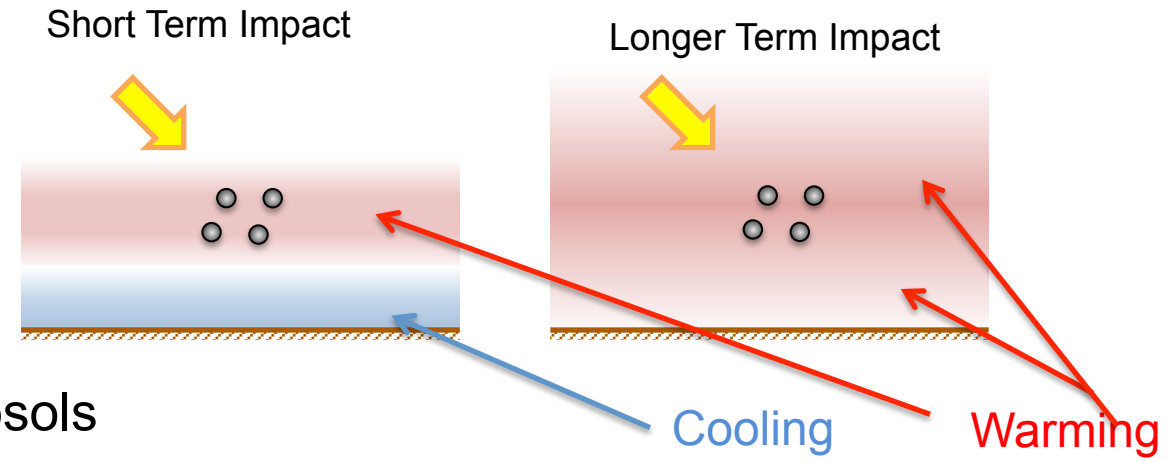
Aerosol Direct Forcing by Scattering Aerosols



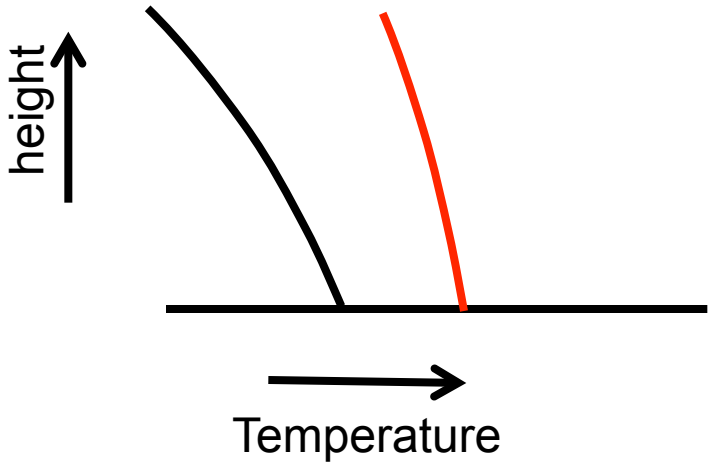
- Scattering Aerosol
  - About the same Forcing the at surface and top of atmosphere
  - General cooling of surface and atmosphere



Aerosol Direct Forcing by Absorbing Aerosols

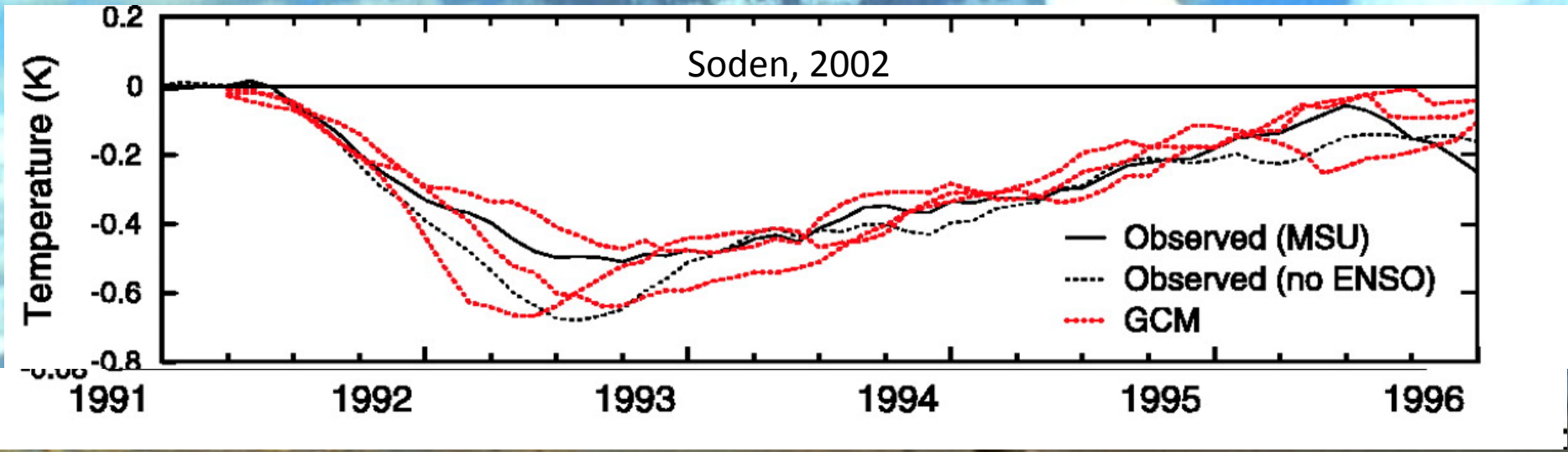


- Absorbing Aerosols
  - Initially heats the atmosphere and cools below aerosol to the surface
  - Later, Absorption & Emission in the longwave, and vertical mixing lead to
    - Warming
    - More Stable Atmosphere
    - Reduce mixing and convection
    - Less evaporation,
    - Less precipitation
- Forcing at Surface larger the Forcing at the Top of Atmosphere



Volcanoes caused global cooling by putting small particles in the stratosphere

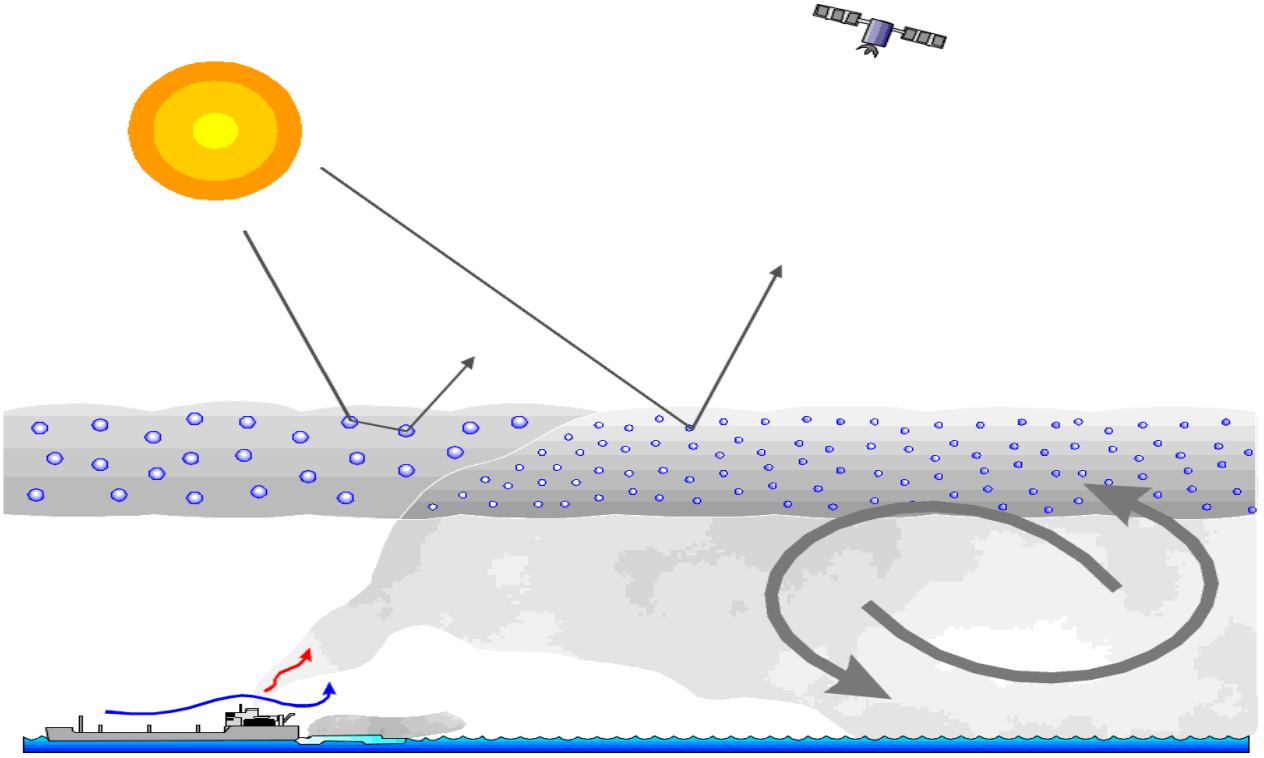
Mt. Pinatubo



USGS

Aerosol Indirect Effects

Clouds upstream of pollution

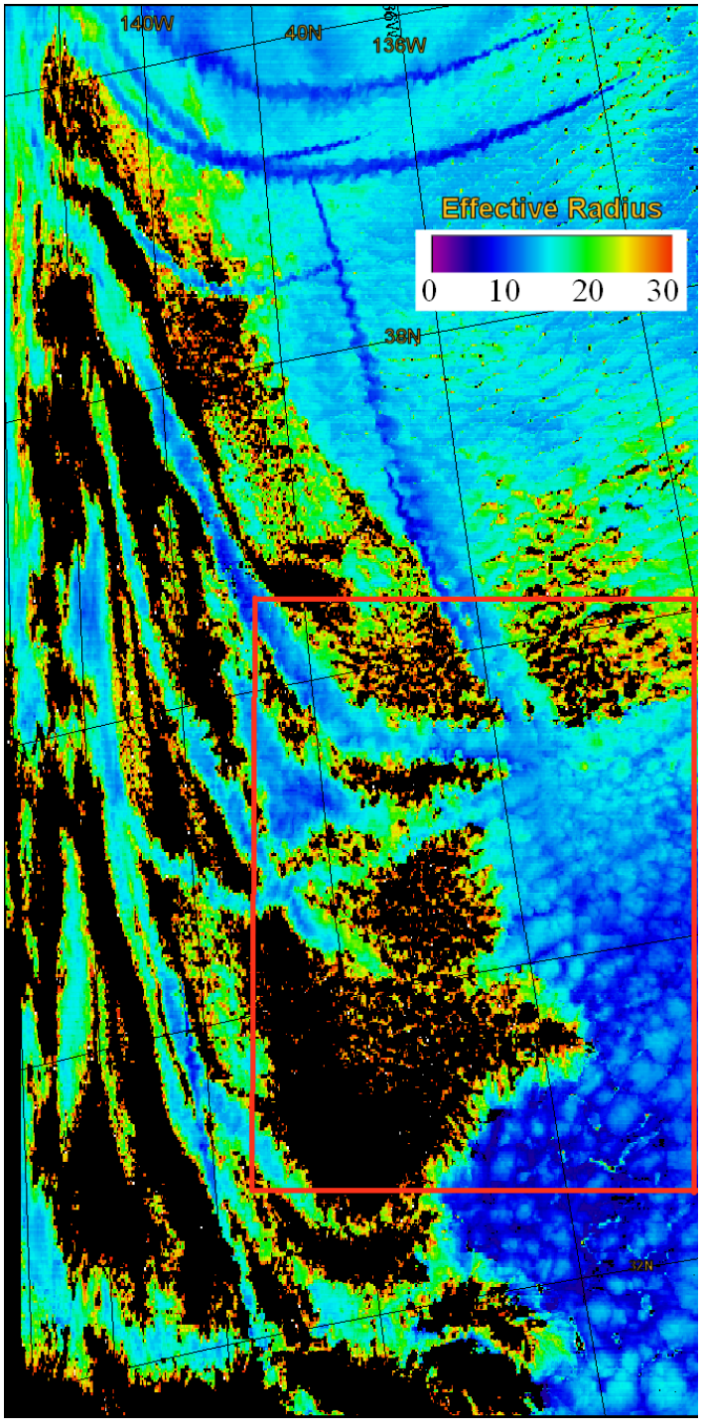


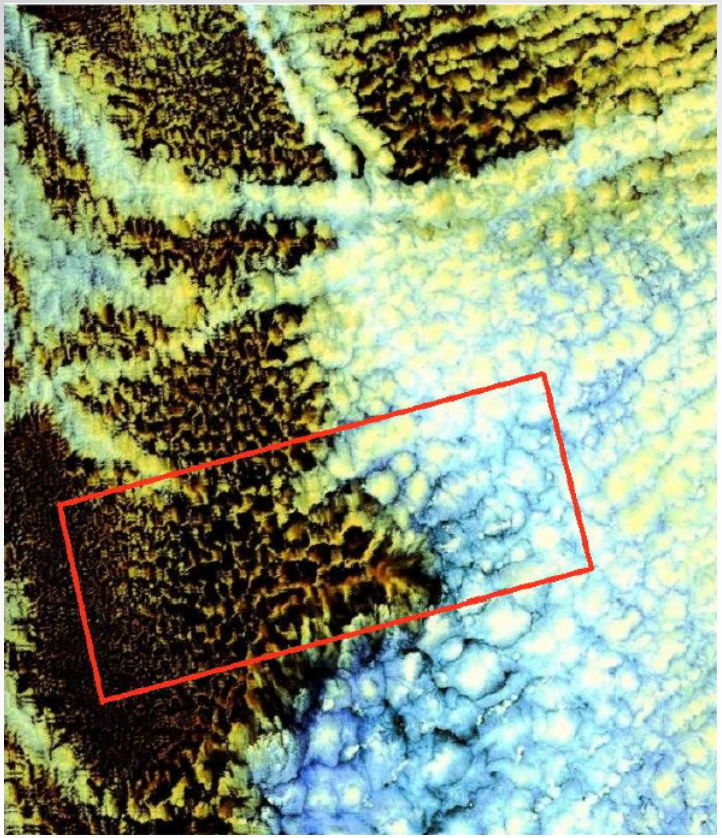
Clouds in the presence of pollution

from D. Rosenfeld

- Particles emissions increase concentration of cloud condensation nuclei (CCN)
- Increased CCN increase concentration of cloud droplets and reduce their avg. size
- Increased concentration and smaller particles reduce production of drizzle
- Liquid water content increases because loss of drizzle particles is suppressed
- Clouds may be optically thick, brighter, last longer, and be more pervasive

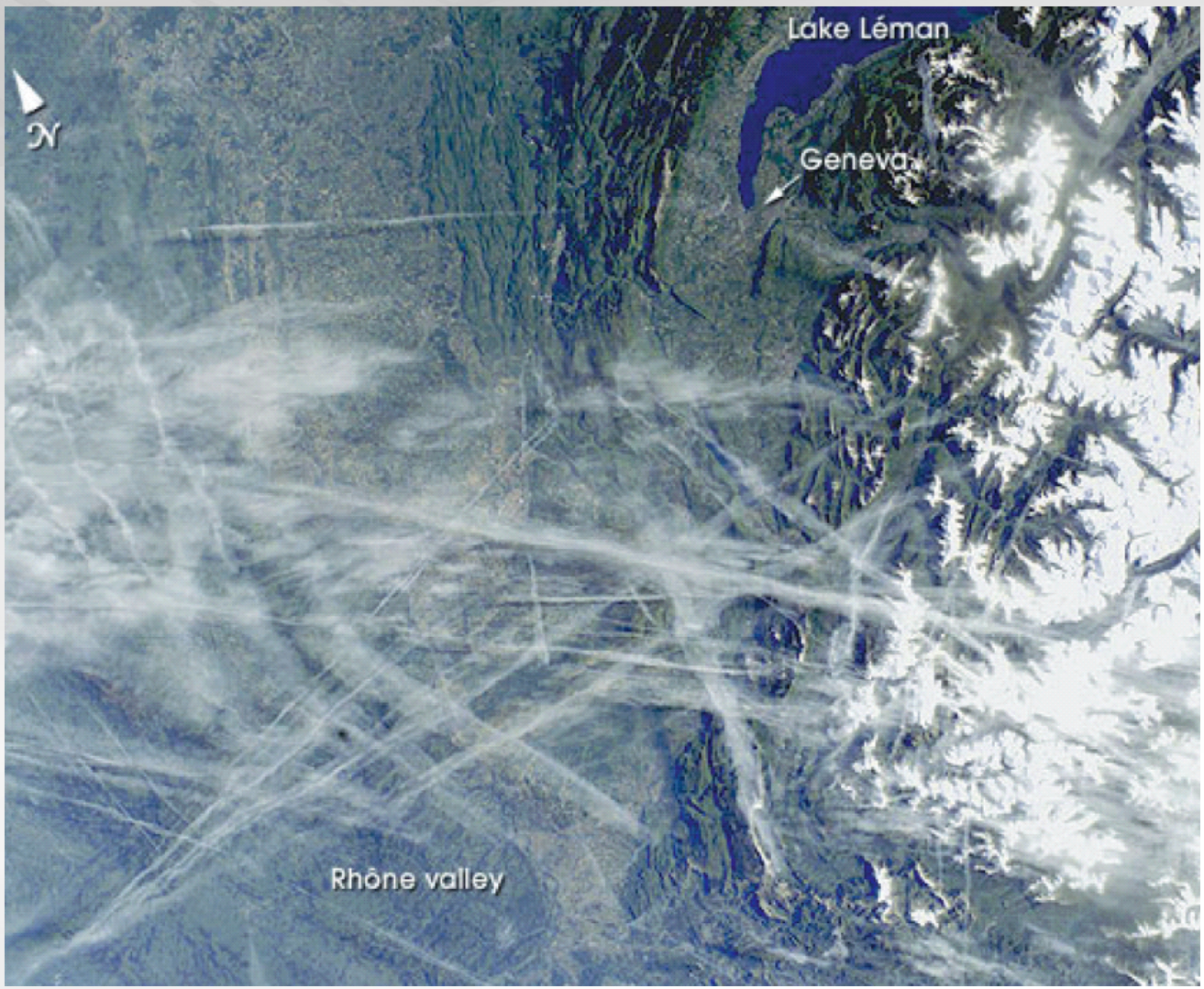
Evidence from Satellite Ship Tracks





Rosenfeld, Kaufman, and Koren, "Switching cloud cover and dynamical regimes from open to closed Benard cells in response to the suppression of precipitation by aerosols", *Atmos. Chem. & Phys. Disc.*, submitted, 2005.

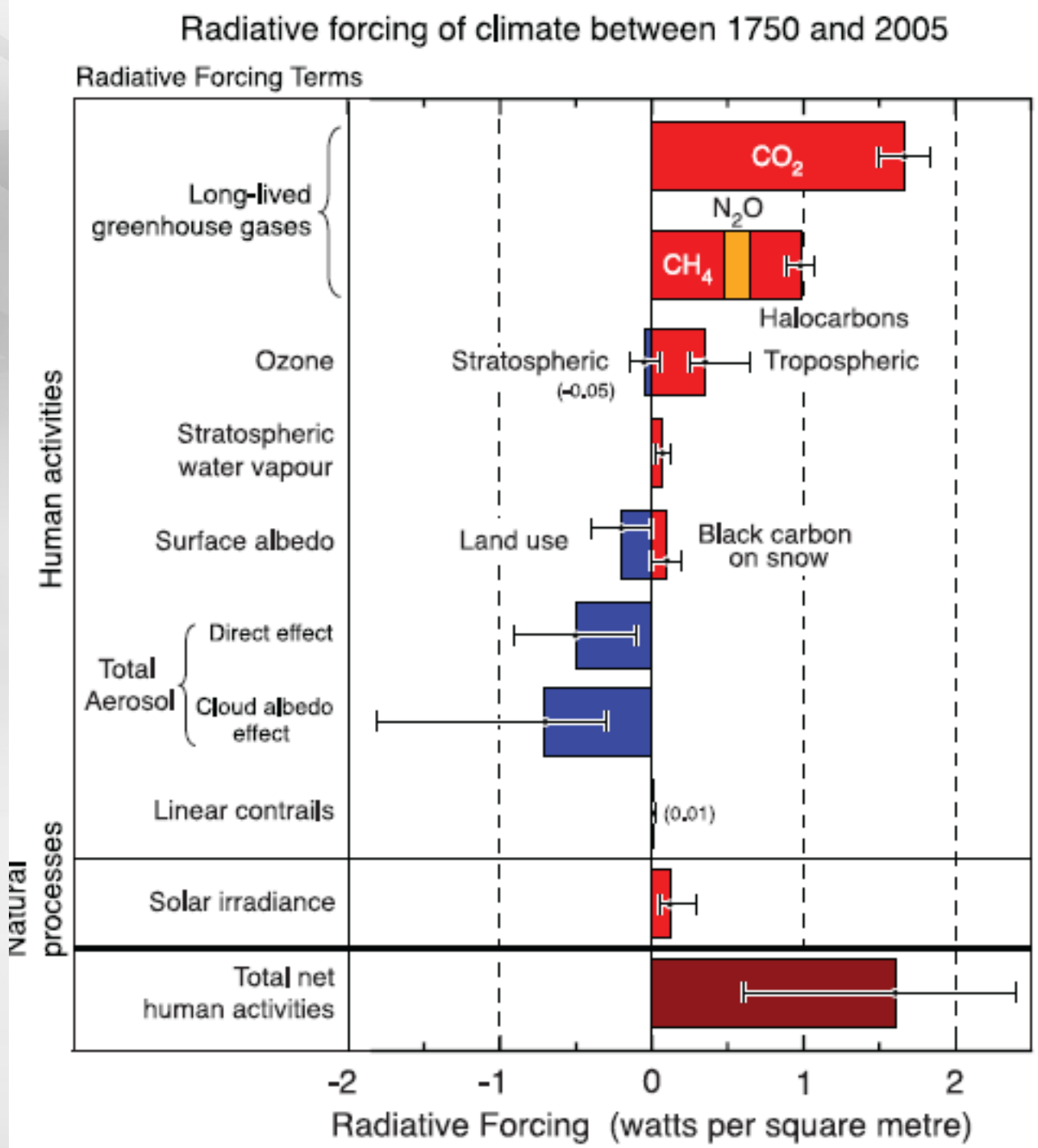
OTHER EVIDENCE OF CLOUD FORCING: CONTRAILS AND "AIRCRAFT CIRRUS"



Aircraft condensation trails (contrails) over France, photographed from the Space Shuttle (©NASA).

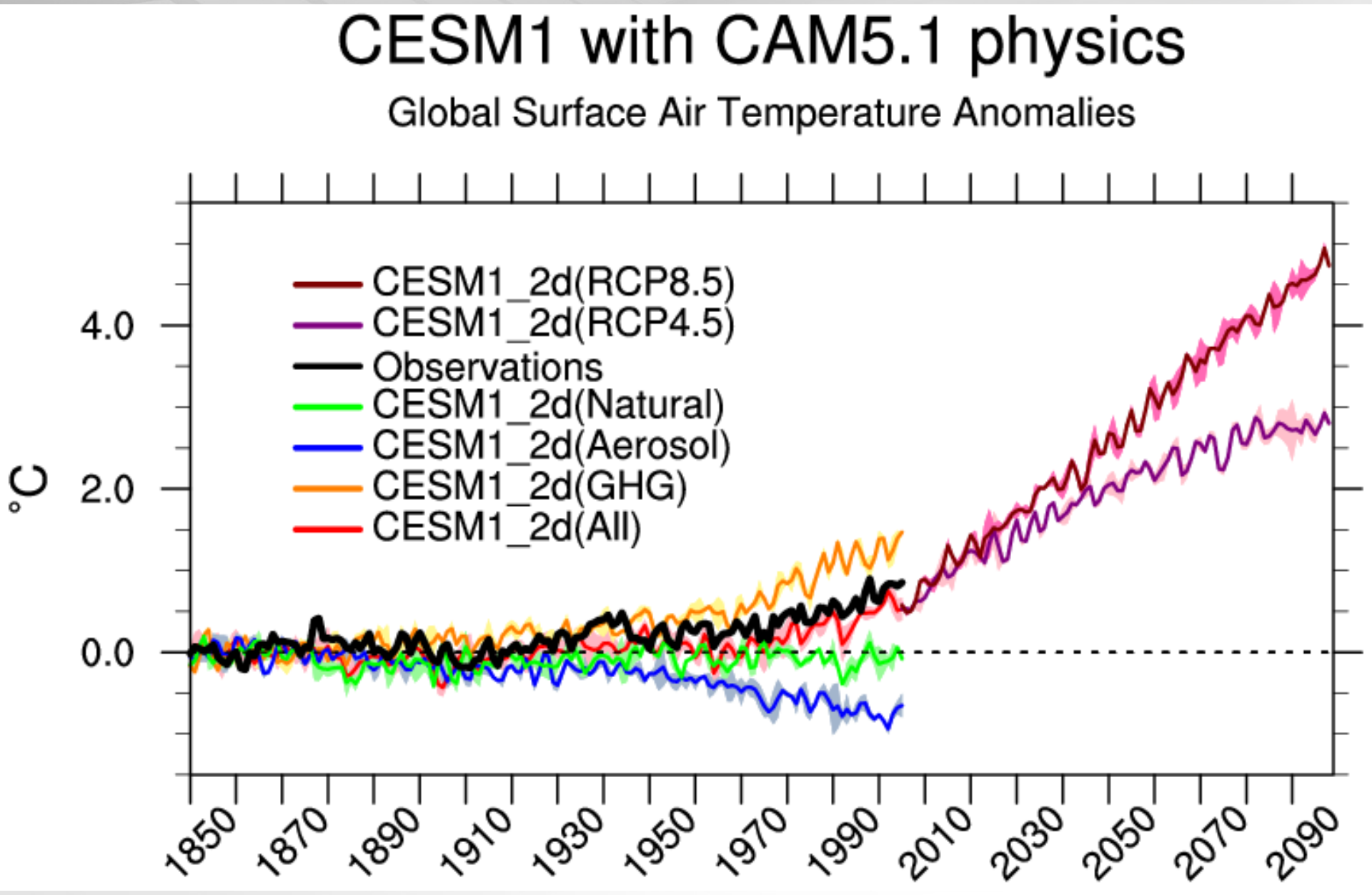
Aerosols Play multiple roles in climate

http://www.geonet.org.nz/news/archives/2007/article-oct-4-2007-mt-ruapehu-activity-update.html

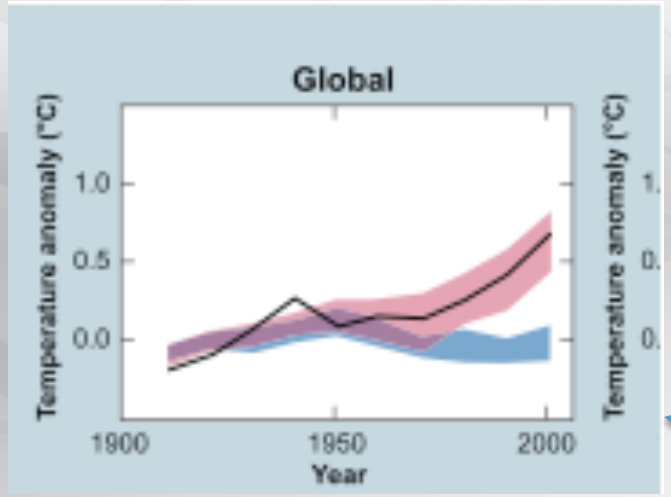

Radiative forcing of climate between 1750 and 2005
Radiative Forcing Terms
Human activities
Natural processes
Long-lived greenhouse gases
CO2
N2O
CH4
Halocarbons
Ozone
Stratospheric
(-0.05)
Tropospheric
Stratospheric water vapour
Surface albedo
Land use
Black carbon on snow
Total Aerosol
Direct effect
Cloud albedo effect
Linear contrails
(0.01)
Solar irradiance
Total net human activities
-2
-1
0
1
2
Radiative Forcing (watts per square metre)

IPCC [2007]

Forcing Agents and Climate Change



Why do we care?

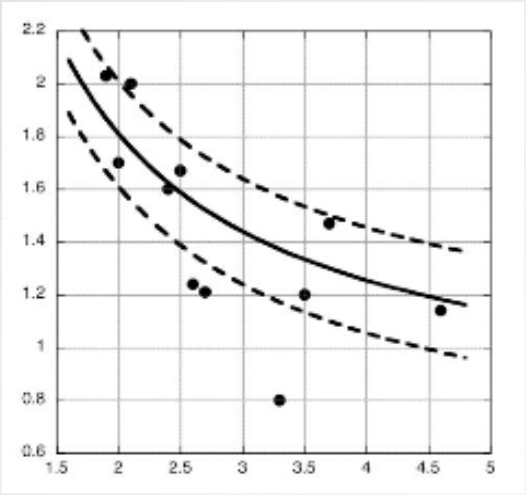


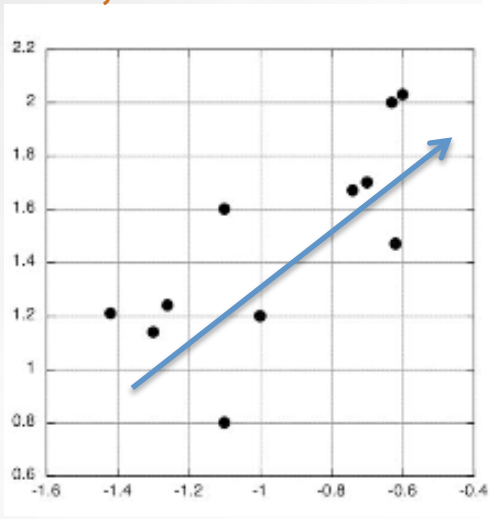
- Many models reproduce the historical trend in T_S when "total" anthropogenic forcings were included
- Some models didn't include aerosol cloud interactions (the "indirect effect")
- Models "forcings" differ by > a factor of 2
- Models "climate sensitivities" differ by > a factor of 2

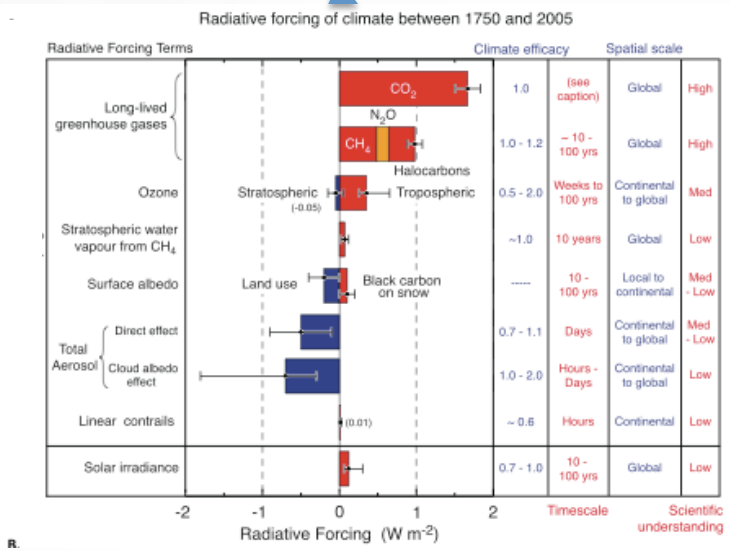
IPCC, AR4

Kiehl, GRL, 2007

Total Forcing







Climate Sensitivity
(how big is the response for a given Forcing)

Aerosol Forcing

Observational Estimates are generally smaller than Climate Model Estimates

Source	Total Aerosol Forcing		
	low	central	high
Murphy et al. (2009)	-1.5 (1σ)	-1.1	-0.7 (1σ)
Andronova and Schlesinger (2001)	-1.3	-0.9	-0.5
Stott et al (2006)	-1.4	-0.9	-0.4
Forest et al (2006)	-0.7	-0.5	-0.1
Shindell & Faluvegi 2009	-1.8	-1.3	-0.8

Formally, most of these estimates are for "everything else" not explicitly included (land-use, stratospheric changes, …).

Murphy et al. is particularly important, since this is an estimate based on observational data, largely independent of GCMs.

Different factors that influence climate have different "fingerprints"

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Temperature change / Century by Forcing Agent

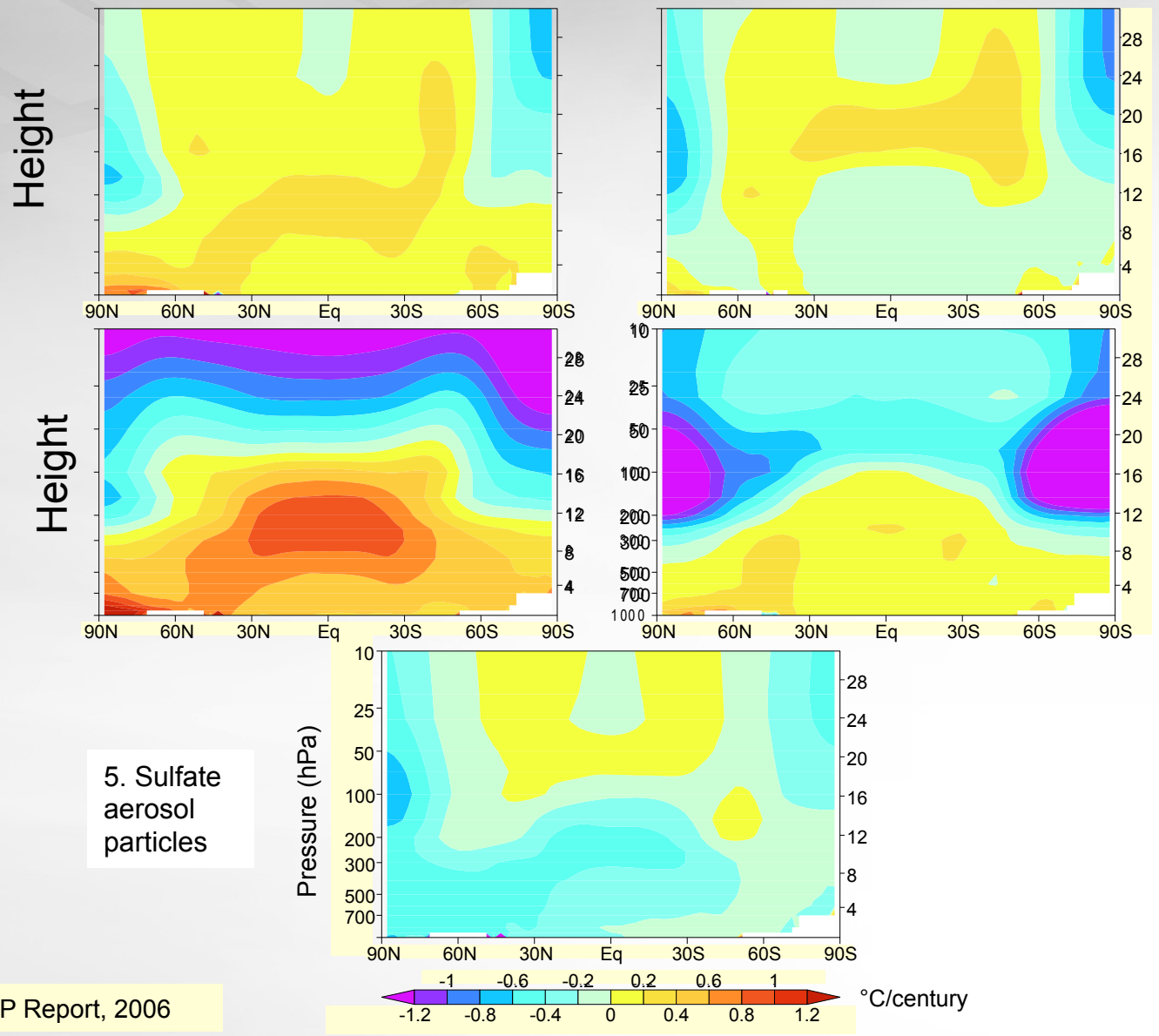
1. Solar

2. Volcanoes

3. Well-mixed greenhouse gases

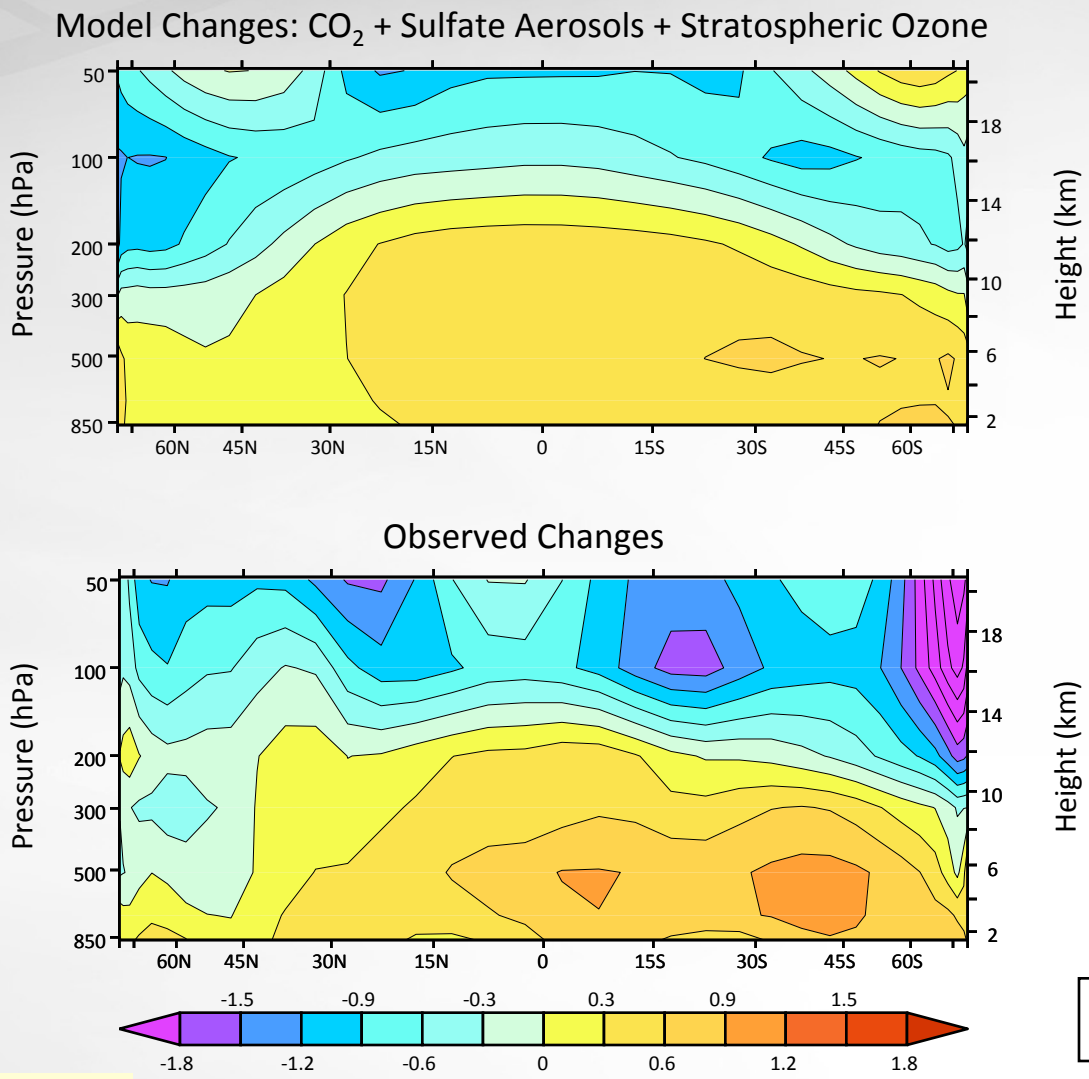
4. Ozone

5. Sulfate aerosol particles



Santer *et al.*, CCSP Report, 2006

“Fingerprinting” with temperature changes in Earth’s atmosphere



Temperature changes in ^{o}C

Santer *et al*., *Nature* (1996)

Take home messages

- Aerosols are needed to explain the 20th C temperature record
- Aerosol forcing is very uncertain
- Our inability to characterize the aerosol forcing for the 20th C confounds our ability to characterize climate sensitivity
- If we don't know climate sensitivity we cannot project climate change

- *The good news*: Most climate models are not "tuned" to reproduce the 20C temperature record. They are tuned for many other things
- *The "less than satisfactory" news*: We don't know what part of tuning process or climate characteristic makes models reside near the "Kiehl Curve"

Aerosol effects are regional (E.g. the direct effect)

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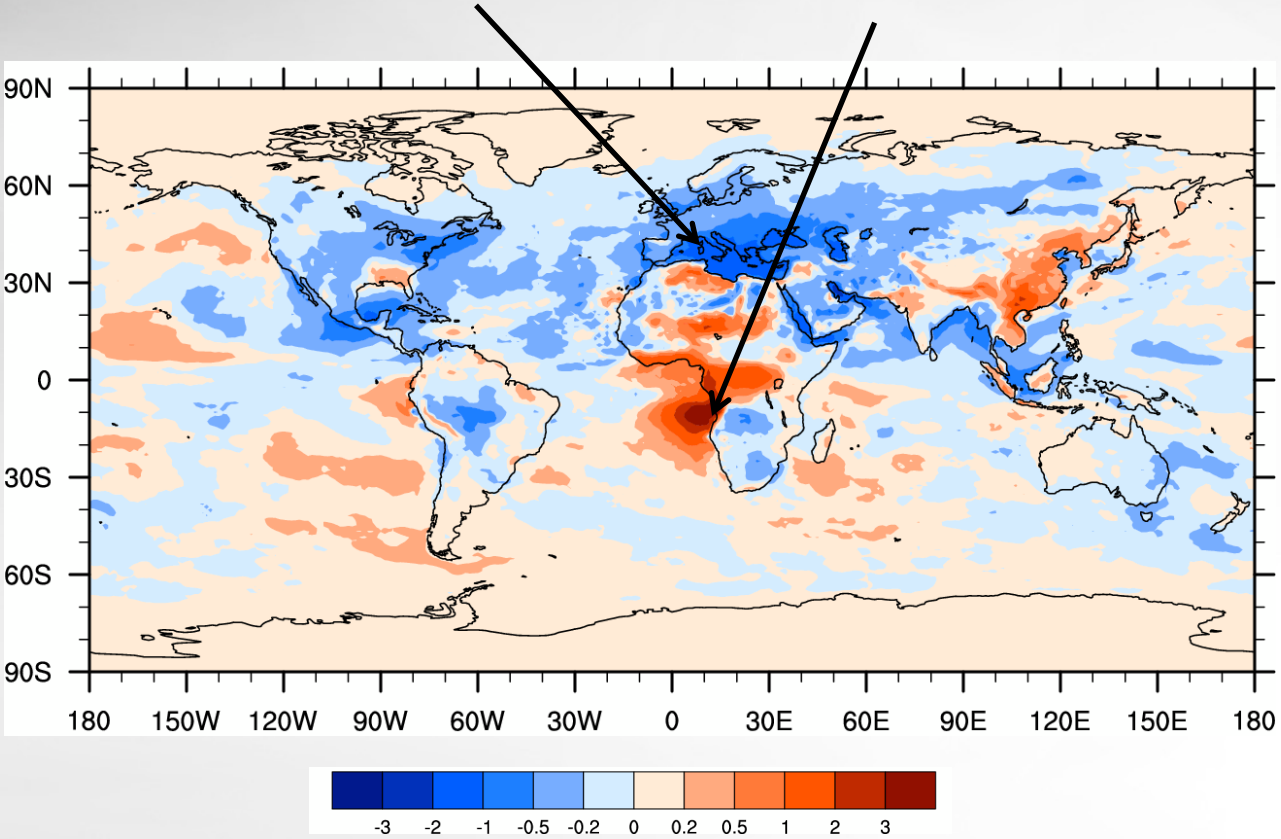
Cooling: Sulfate aerosol accumulate over dark surface (Ex: Mediterranean)

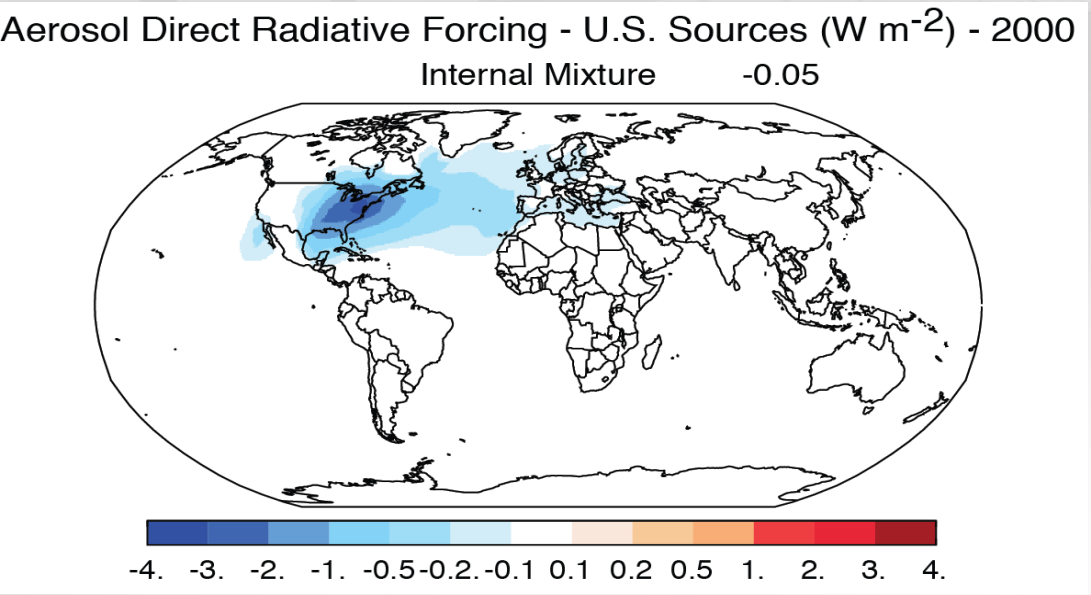
Warming: black carbon accumulate over bright surface (Ex: Biomass burning in Africa)

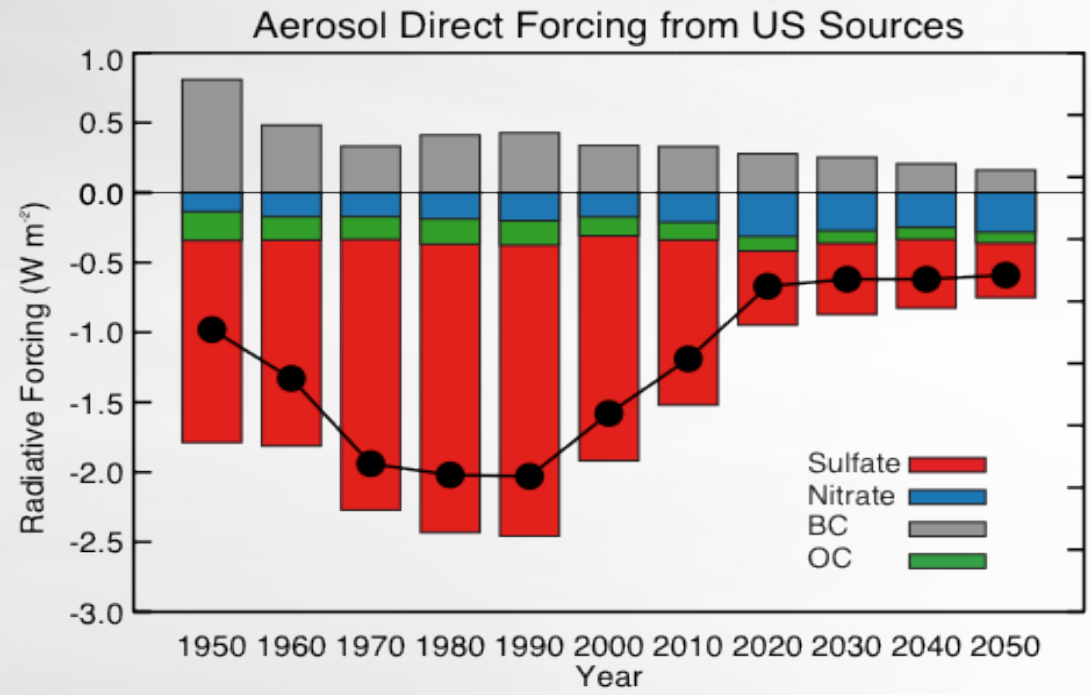


Direct forcing:
0.01 W/m^2

Small forcing because enhanced black carbon warming

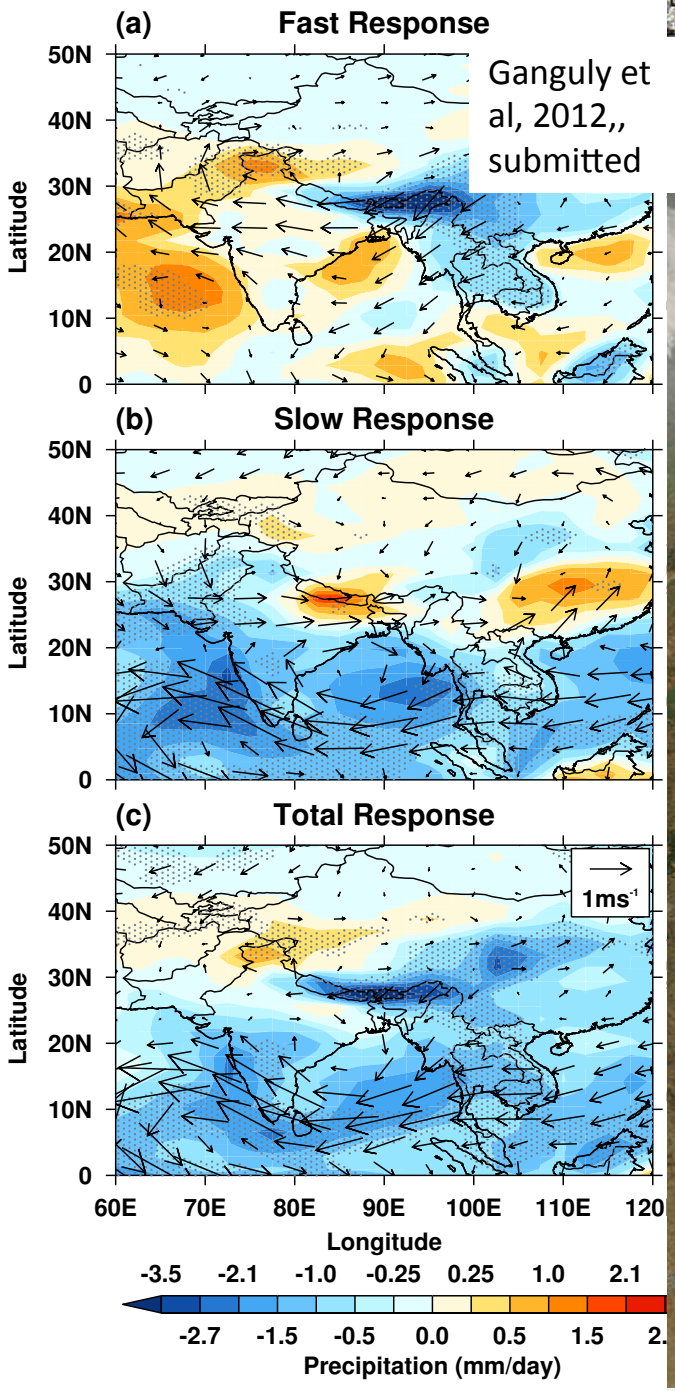
Radiative forcing from US anthropogenic aerosol





- Forcing is mostly from sulfate, peaked in 1970-1990
- Little leverage to be had from BC control

Leibensperger et al., ACP.

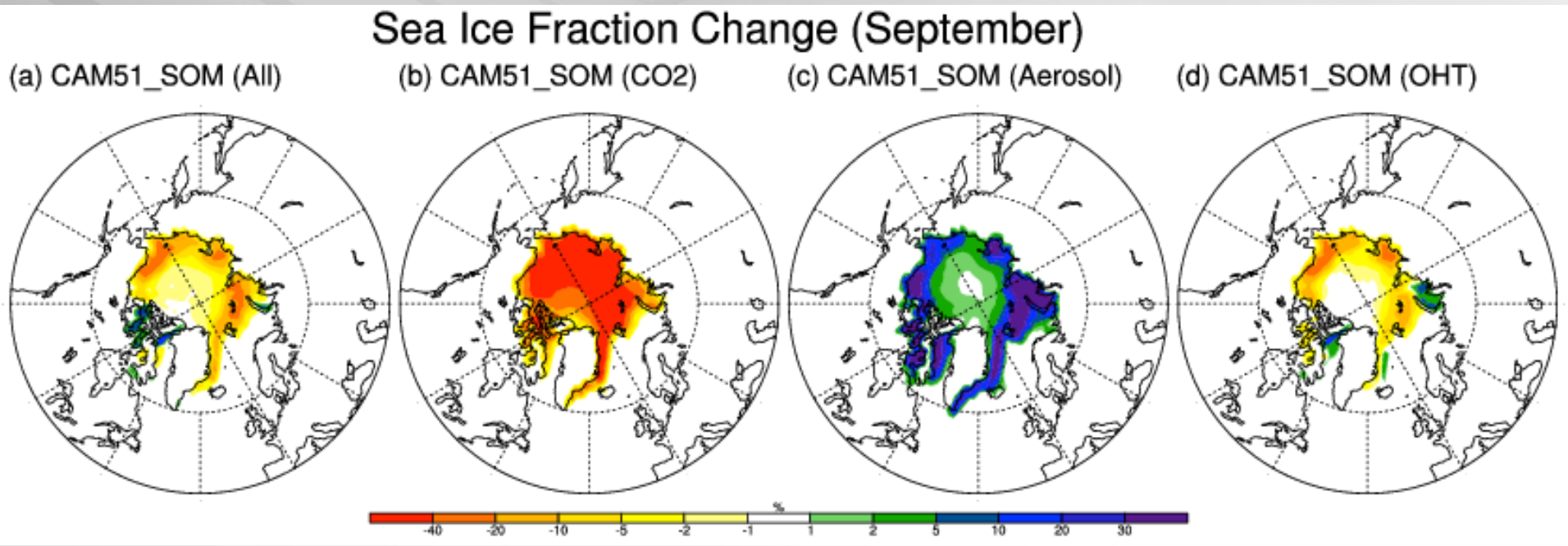


Ganguly et al, 2012,, submitted

Monsoons --- A complex system involving Aerosols

- Depends upon aerosols location (over land/ocean, near Himalayas, altitude)
- Depends upon scattering and absorption properties *and models currently are not definitive about which is more important*
- Depends on direct and indirect effects *and ditto*
- Affects precipitation, riverflow, agriculture, habitabiity, health, energy,

Teasing out the role of aerosols on sea ice change (Yoon, et al, 2012, in prep)



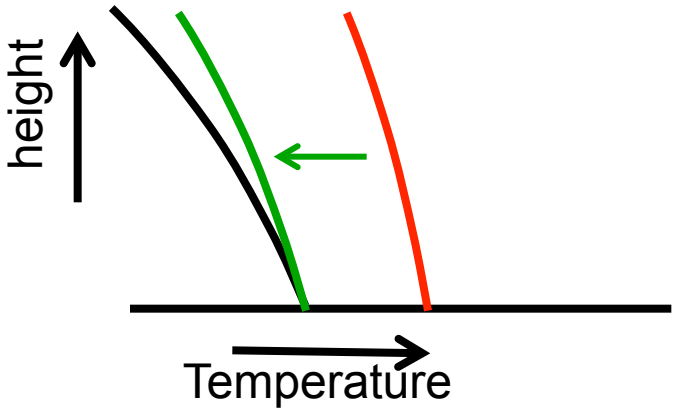
- Ocean Heat Transport is important in modulating the response to other forcings

The Inexact compensation of short and Longwave Forcing -- Precipitation

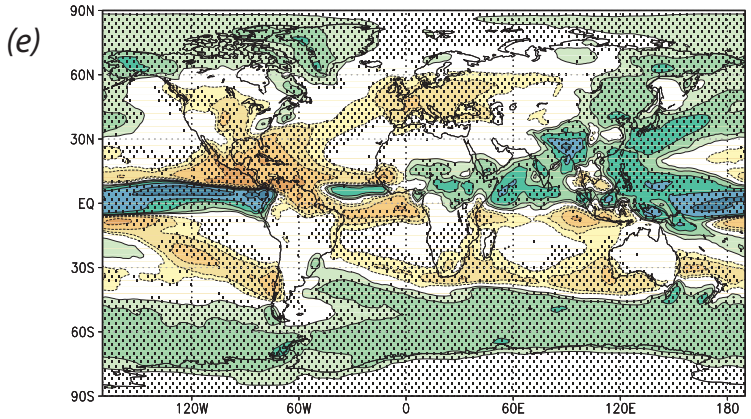
GeoMIP

(Geoengineering Model Intercomparison study, Kravitz, 2011)

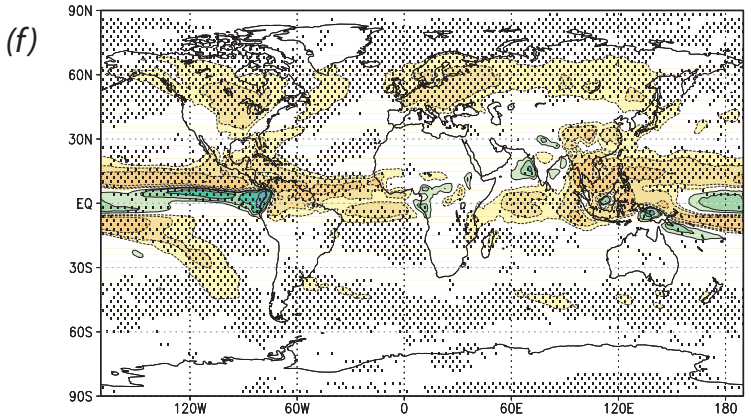
Even relatively uniform aerosol distributions do not "cancel" GHG forcings

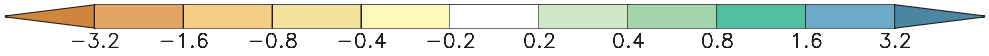


2xCO2 precipitation change



2xCO2+ Nearly Uniform Aerosols





Take Home Messages

- Emissions impact more than just temperature
  - Precipitation, Sea Ice, Health, Agricultural productivity, many aspects of importance to society
- Non- GHG forcers have global impacts but lifetimes of days to weeks (aerosols, ozone, others). They have local impacts that are likely to matter to IAMs
- It matters whether forcing is by “absorbing” or “scattering” aerosols
- The aerosol source (by sector, by aerosol type) matter also affects the way it interacts with clouds (more tomorrow)

- Aerosols are required to explain the 20th C temperature record
- Aerosol forcing is very uncertain
- Our inability to characterize the aerosol forcing for the 20th C confounds our ability to characterize climate sensitivity
- If we don’t know climate sensitivity we cannot project climate change
- *Aerosols are important to climate change*

Extra Slides

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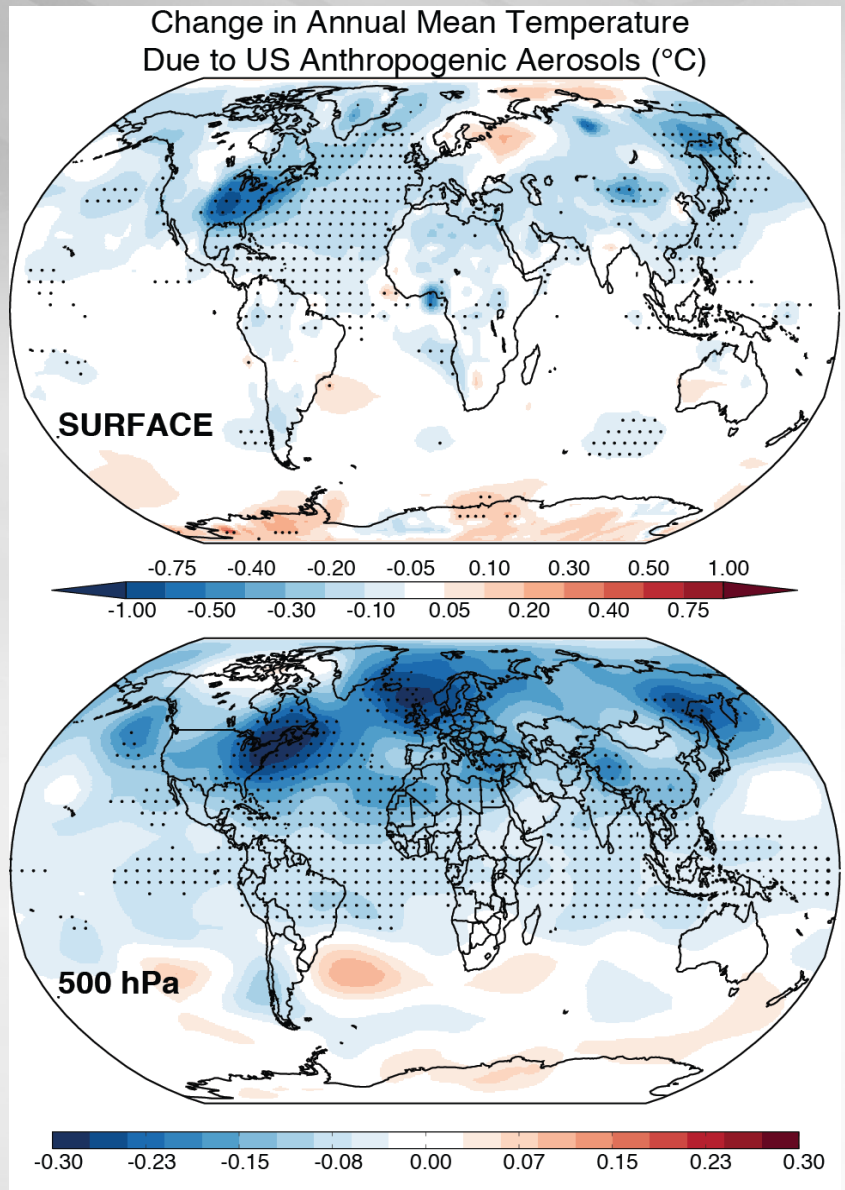
Cooling due to US anthropogenic aerosols in 1970-1990

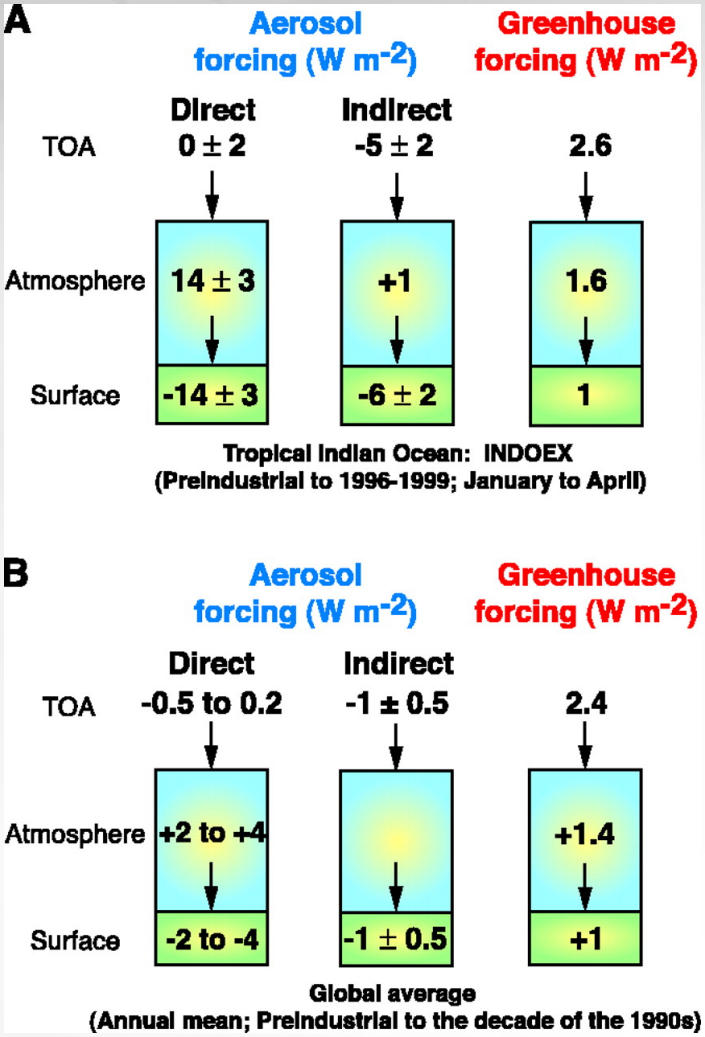
From difference of GCM simulations with vs. without US aerosol sources, including aerosol direct and indirect radiative effects



- Surface cooling (up to 1° C) is concentrated over eastern US
- Cooling at 500 hPa is more widespread over the northern hemisphere

Leibensperger et al., in prep.

Figure 4 Comparison of anthropogenic aerosol forcing with greenhouse forcing.



V Ramanathan et al. Science 2001;294:2119-2124