The role of solar absorption in climate and climate change

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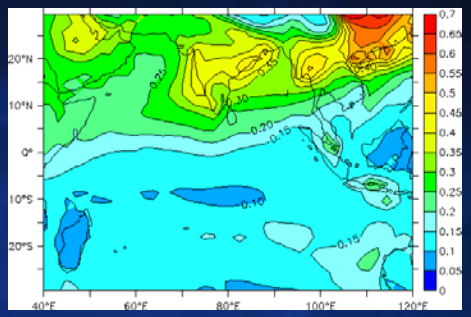
Prior Research on Absorption and Climate

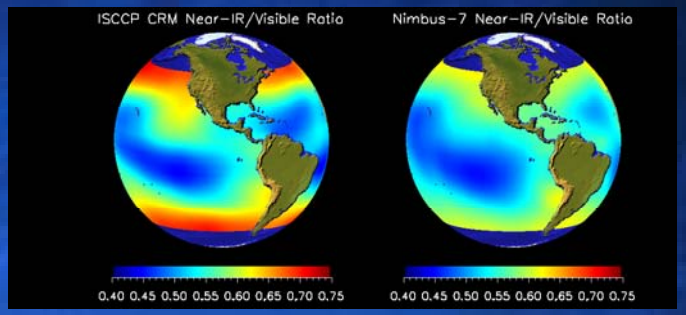
Field Experiments:

- Central Equatorial Pacific Experiment
- Indian Ocean Experiment



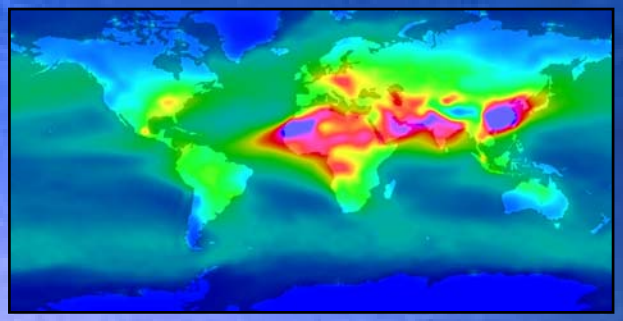
Modeling studies of clouds:

- The color of the planet
- Climate with enhanced cloud absorption

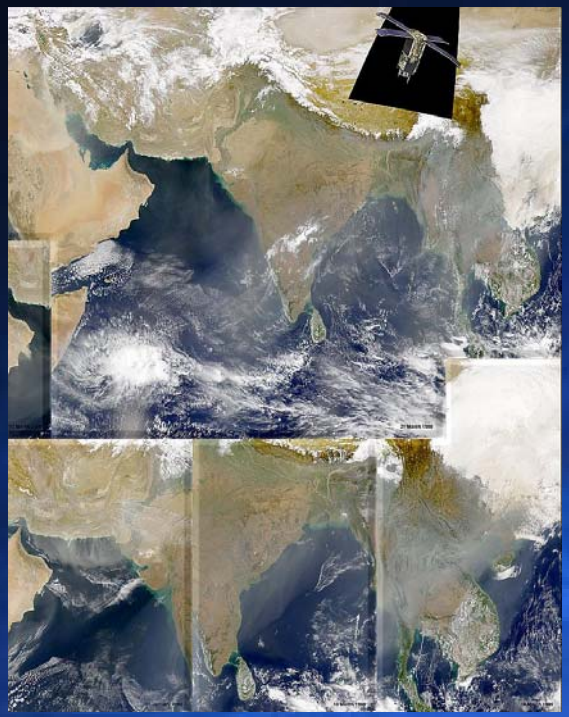


Synthesis of models and aerosol observations:

- Development of aerosol assimilation
- Application to aerosol/climate interactions

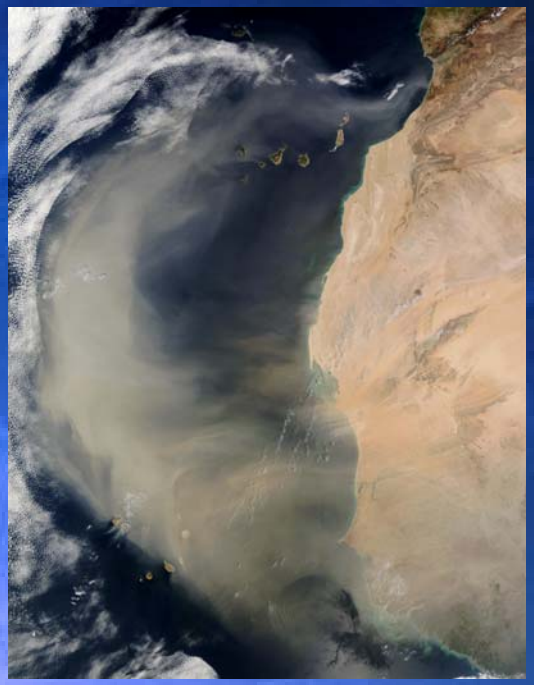


Natural and anthropogenic aerosols



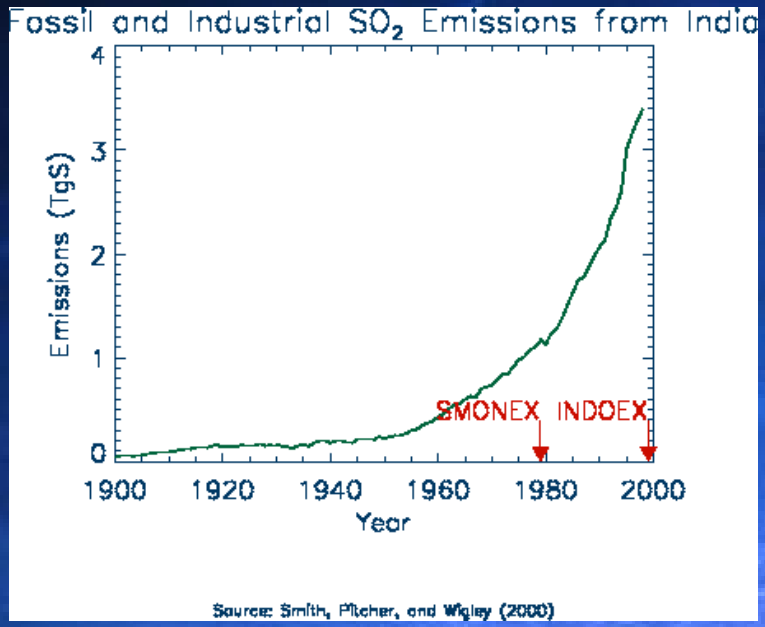
India, March 2000

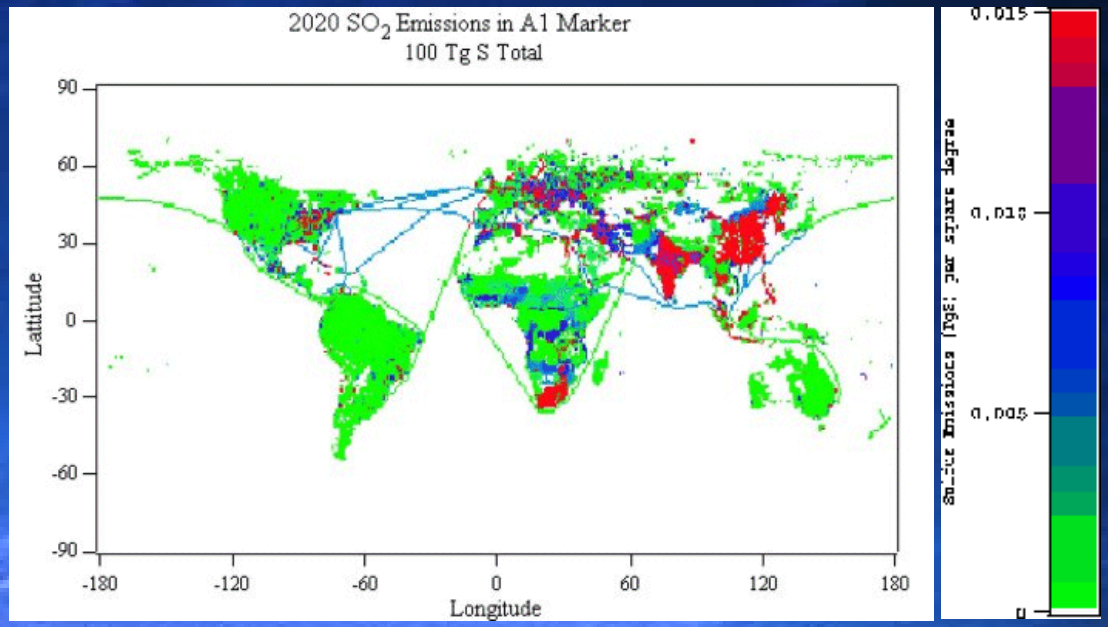
California, October 2003



Africa, March 2003

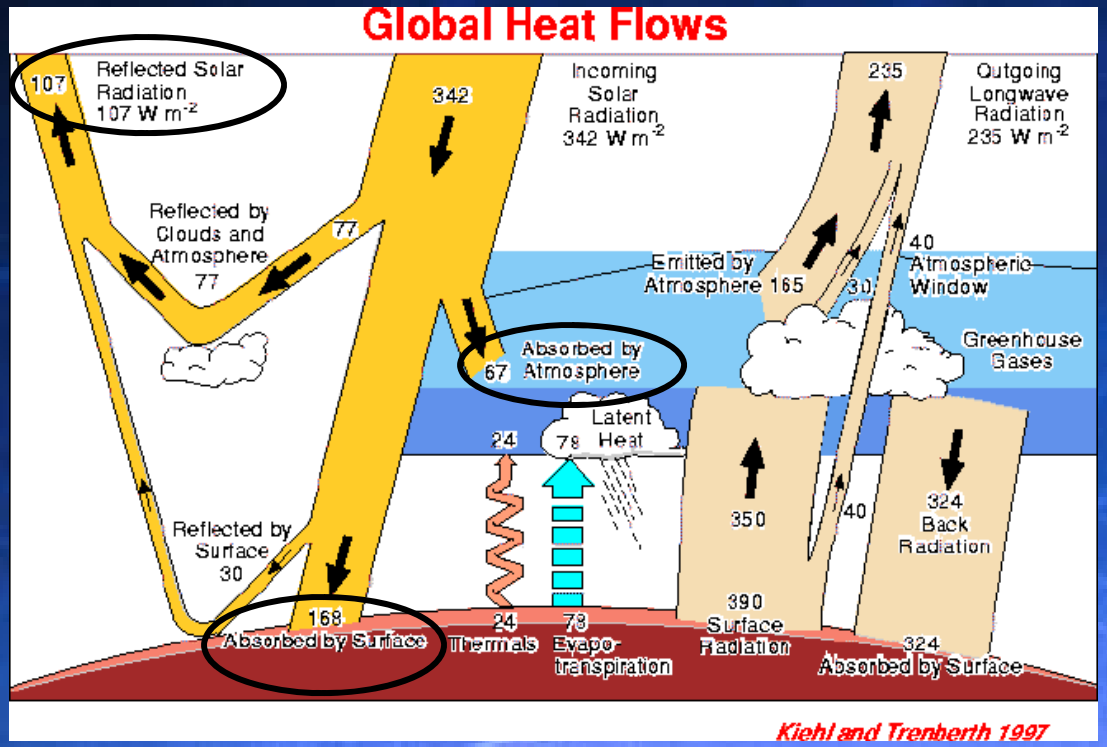
Historical and projected sulfate emissions





- Emissions from India have tripled in last 20 years of 20th century..
- Asia is projected to dominate aerosol emissions by 2020.

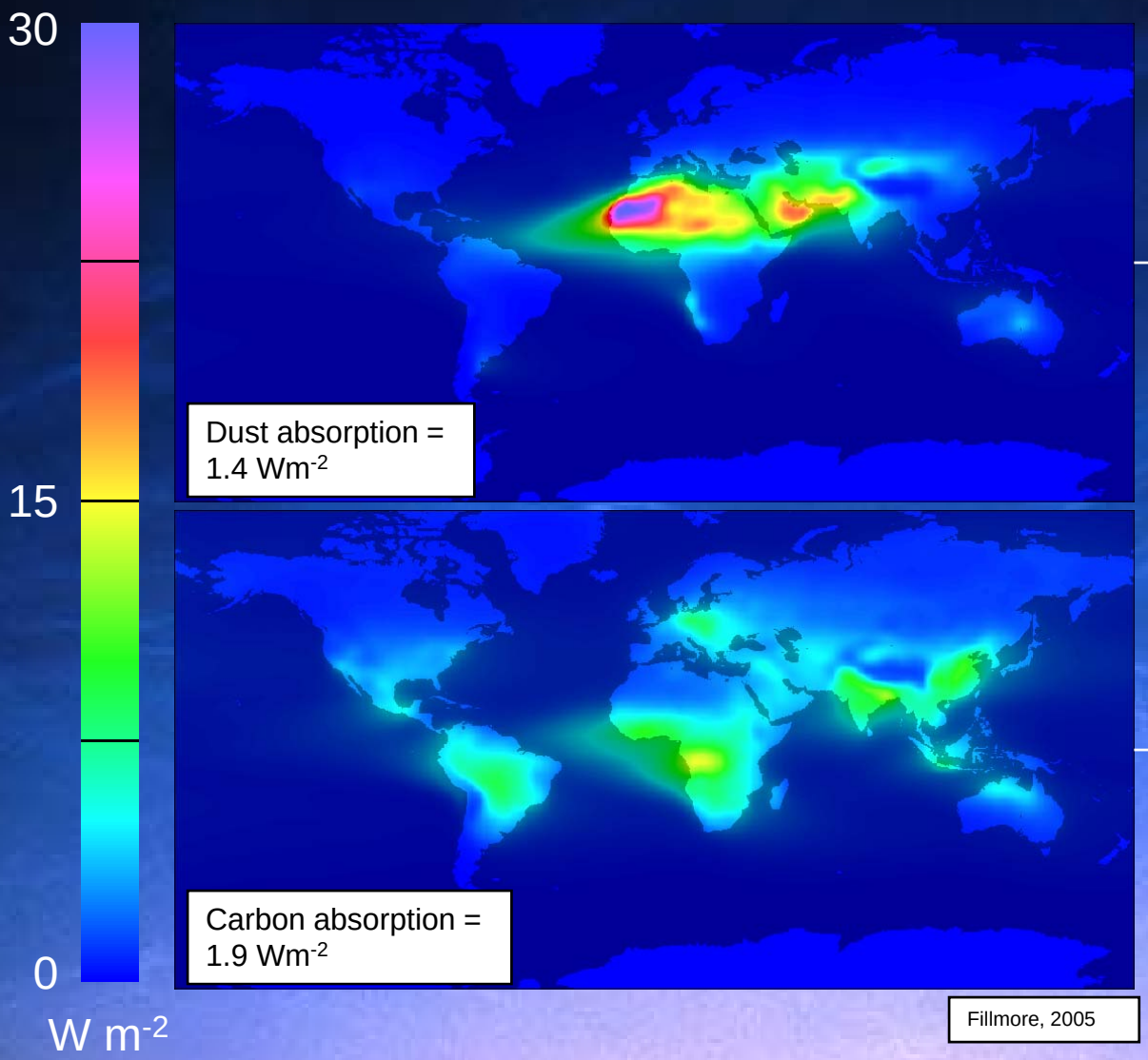
The energy budget of the Earth's climate



Gas	Absorption
CO_2	1
O_2	2
O_3	14
H_2O	43

- Aerosols alter the radiative energy budget of the climate.
- We will focus on solar reflection, absorption, and transmission.

Magnitude of aerosol absorption



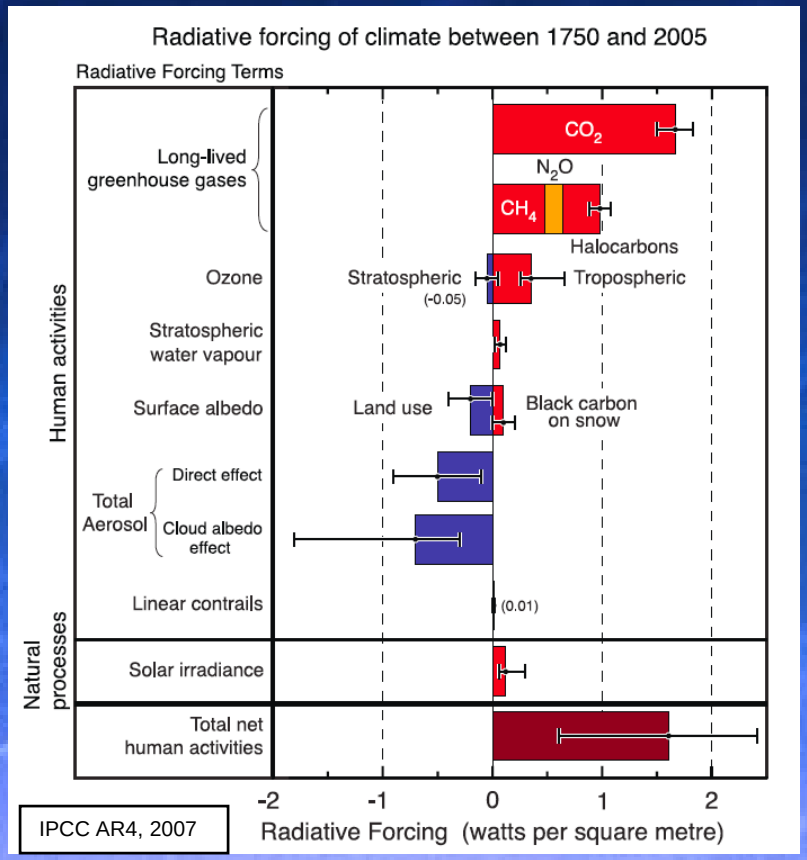
Fillmore, 2005

Gas	Absorption
CO_2	1
O_2	2
O_3	14
H_2O	43

- Collectively, aerosols are 3rd most significant absorber.

Contribution of aerosols to climate forcing

Radiative forcing is an "externally imposed perturbation in the radiative energy budget of the Earth's climate system." (IPCC TAR)



IPCC AR4, 2007

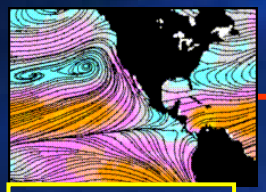
Probability that historical forcing > 0 is very likely (90%+). However, confidence in short-lived agents is still low at best.

Structure of the talk

- Modeling framework for aerosol/climate interactions
- Aerosol radiative forcing from a hybrid aerosol model
- Changes to surface and atmosphere by aerosols
- Climate sensitivity to changes in aerosols and CO_2
- Effects of aerosols on the hydrological cycle
- Shortwave absorption by methane missing from climate models
- Significant effects by this absorption

Modeling Framework

Emissions Data



Met. Analysis

Chemical Transport Models

Aerosol concentration q

Aerosol Optical Models

Optical depth

Atmospheric State

Radiative Transfer Models

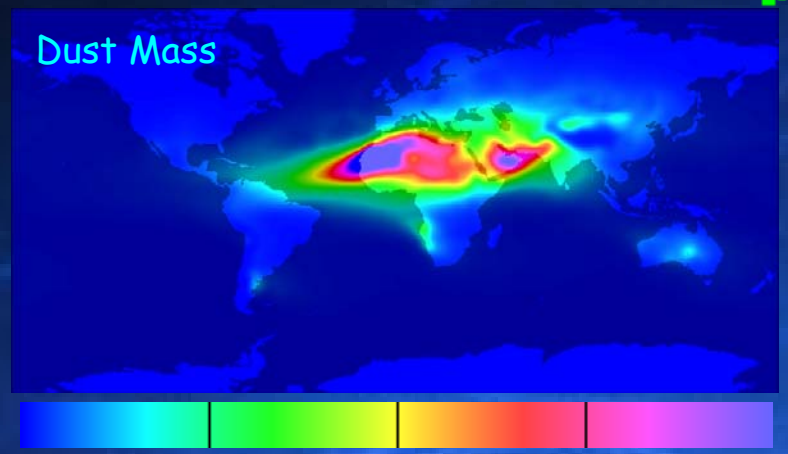
Radiative Forcing

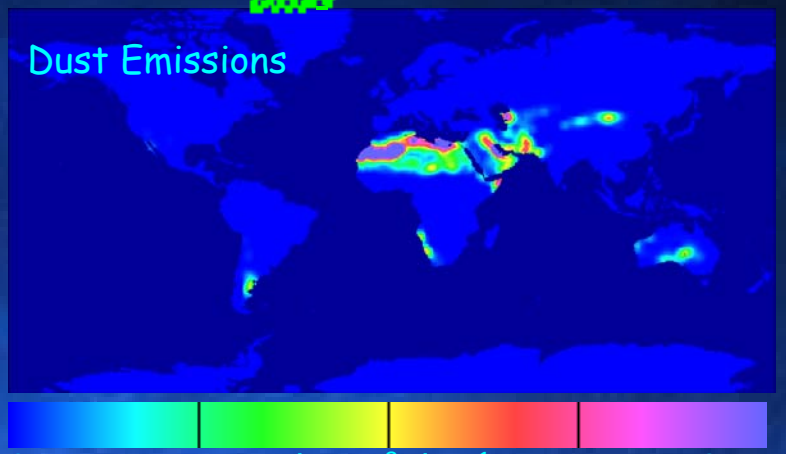
Slab-Ocean Models

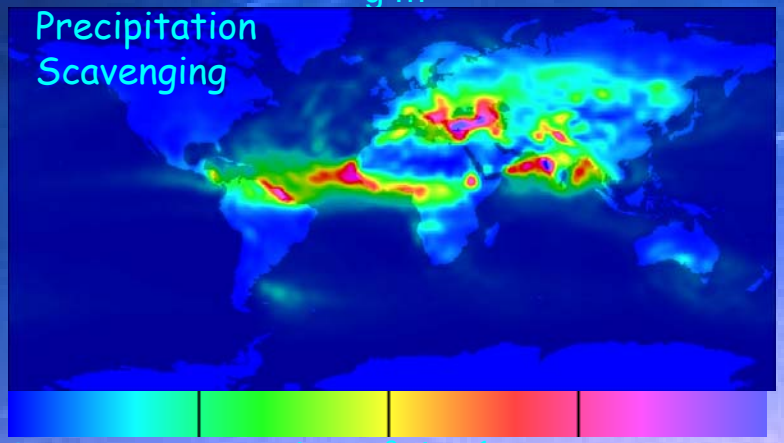
Fully Coupled Models

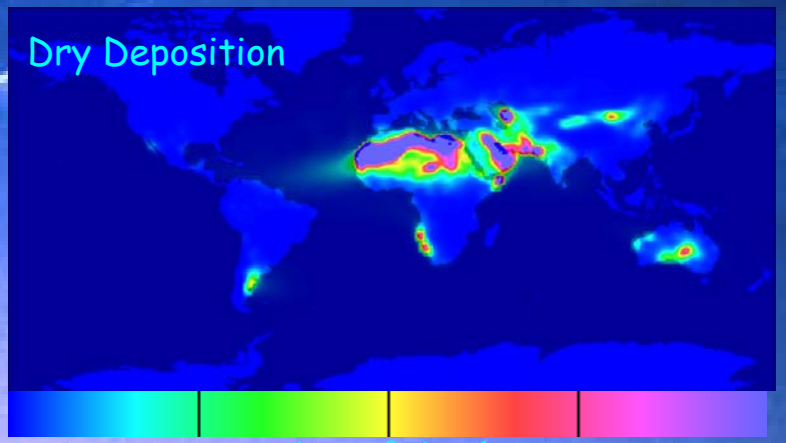
Chemical Transport Models

$$\frac{\partial q_i}{\partial t} + \nabla \cdot (q_i \vec{v}) = \underbrace{S_{emis} + S_{chem}}_{\text{Sources}} \underbrace{- \tilde{S}_{wet} - \tilde{S}_{dry} - \tilde{S}_{chem}}_{\text{Sinks}}$$

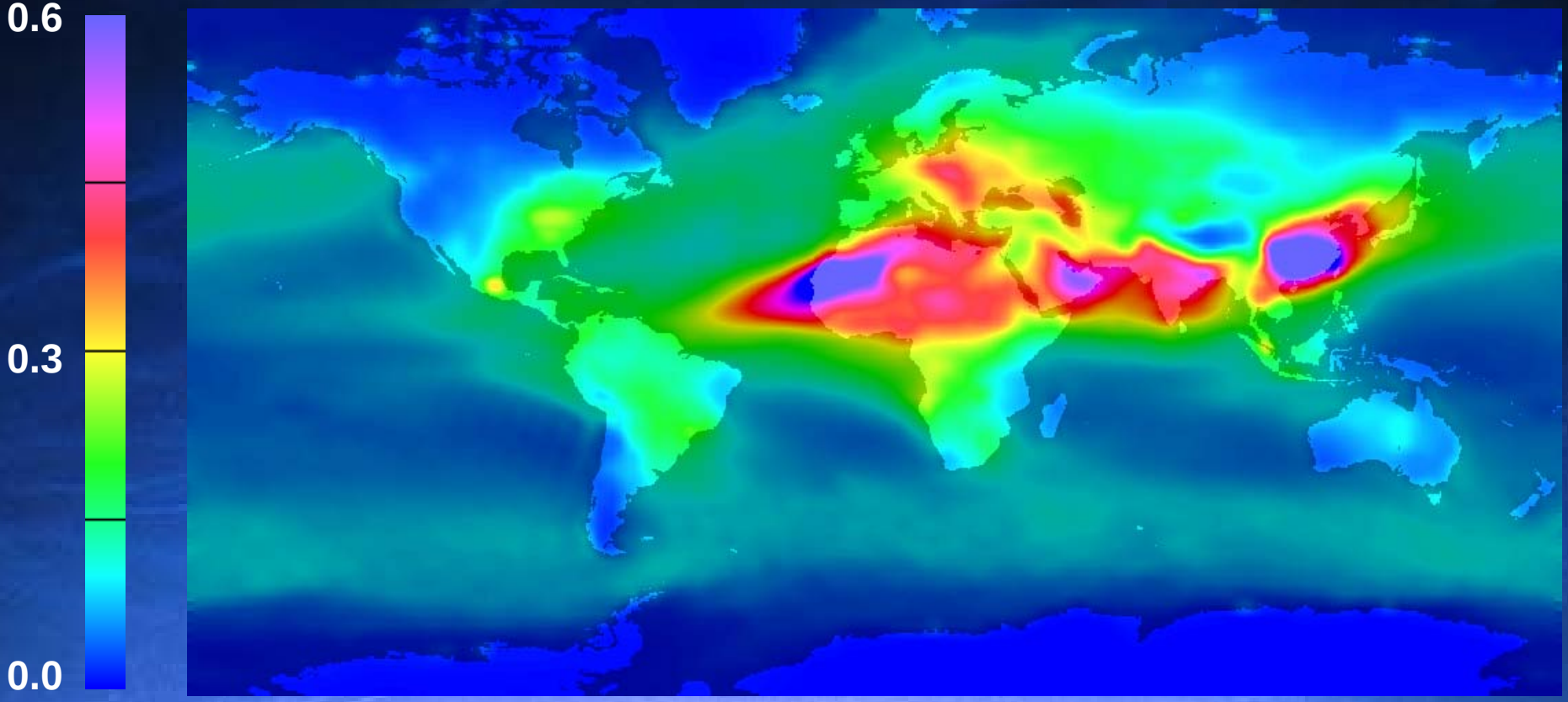








Simulated aerosol optical depth for 2001



Global Aerosol Model Intercomparison: AEROCOM

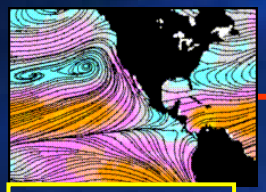
- Targets of intercomparison:
  - Global mass and optical depth
  - Optical properties
  - Fine/coarse mode partitioning
  - Radiative forcing (new)
  - Cloud properties (new)
- Simulations:
  - Standard emissions: 1996-2001
  - Fixed emissions: 2000
- Participants:
  - 14 nudged GCMs and CTMs

Intercomparison of Optical Depths

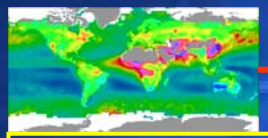
Species	Median AOD	Max/ Min
Sulfate	0.030	2.7
Black Carbon	0.003	3.2
Organic Carbon	0.016	2.1
Dust	0.027	4.1
Seasalt	0.031	3.6
All	0.121	1.9

Details on Modeling Configuration

Emissions Data



Met. Analysis



Satellite Aerosol Data

Atmospheric State

Chemical Transport Models — **Transport & Chemistry (MATCH)**

Aerosol concentration q_i

Aerosol Optical Models — **der; BC/OC/Sea-salt:OPAC**

Optical depth

Radiative Transfer Models — **erization**

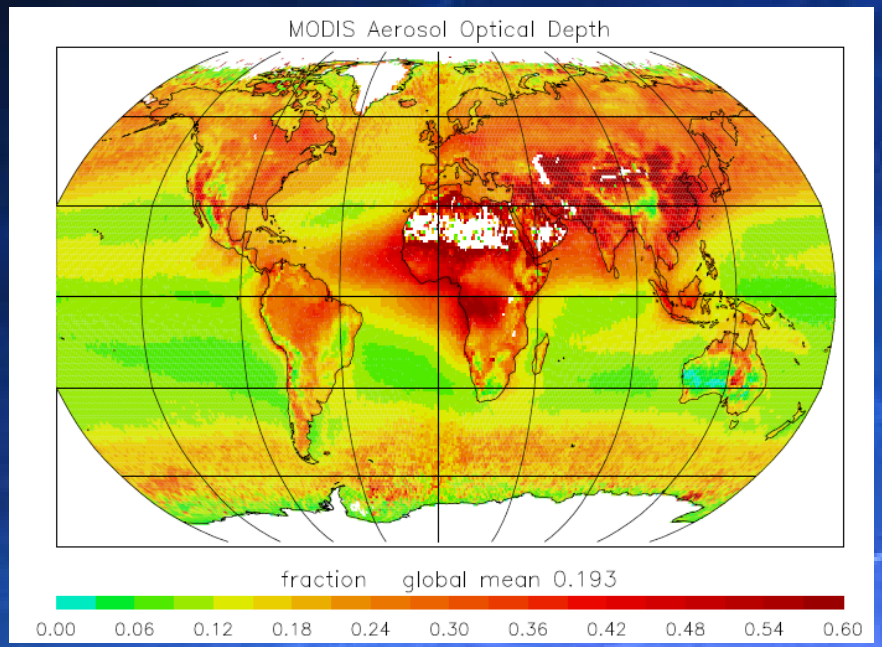
Radiative Forcing

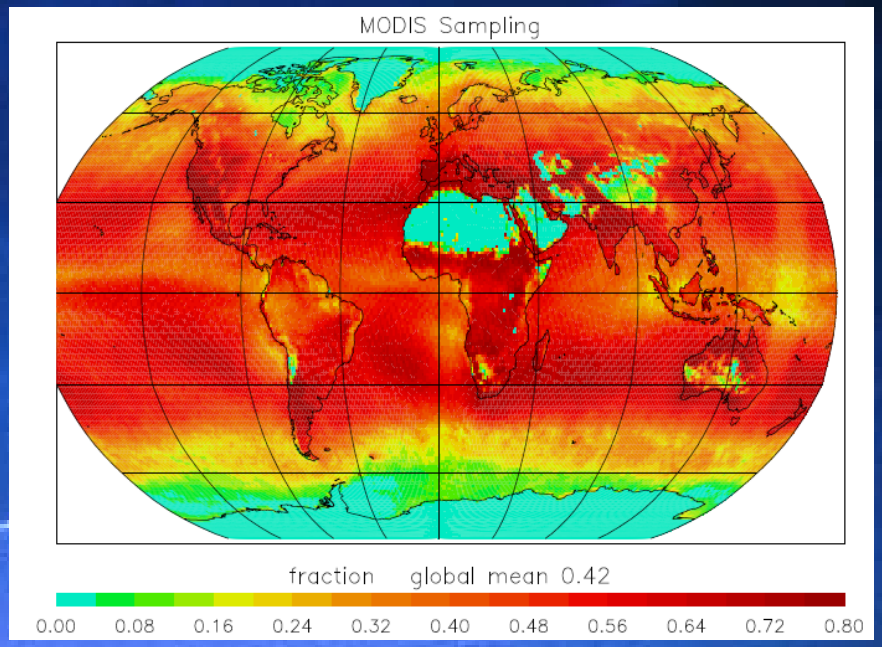
- **CAM3 + SOM**
- **CCSM3** — **pled Models**

References:

- MATCH transport model for aerosols:
  - *Collins et al, 2001, 2002; Rasch et al, 2001*
- Radiative parameterization for CAM3 GCM:
  - *Collins et al, 2001, 2002, 2005, 2006*
- Atmospheric GCM CAM3:
  - *Collins et al, 2004, 2006*
- MODIS assimilation:
  - *Fillmore, 2005*

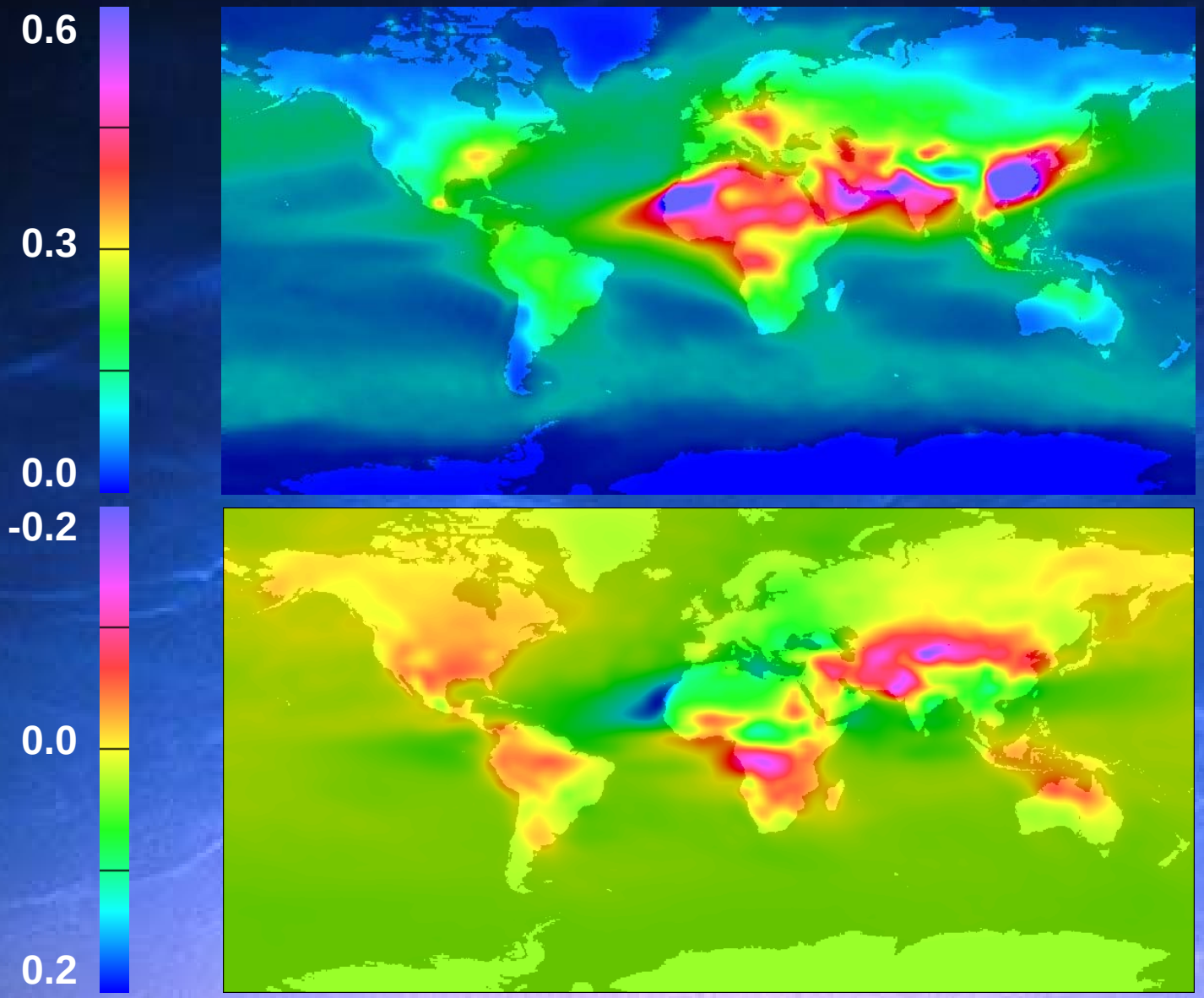
Aerosol Optical Depths:
Moderate Resolution Imaging Spectrometer (MODIS)





(3/2000-2/2003, Level 3, Version IV)

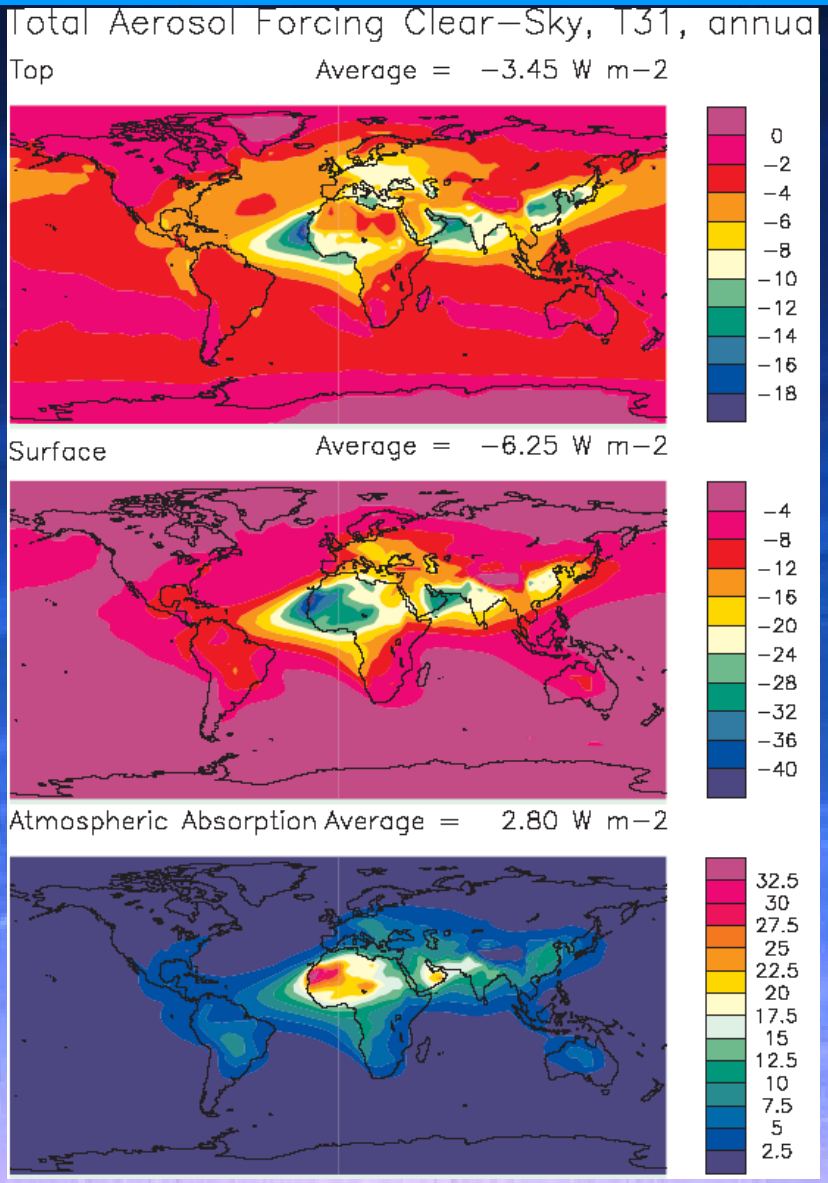
Aerosol Optical Depths for 2001



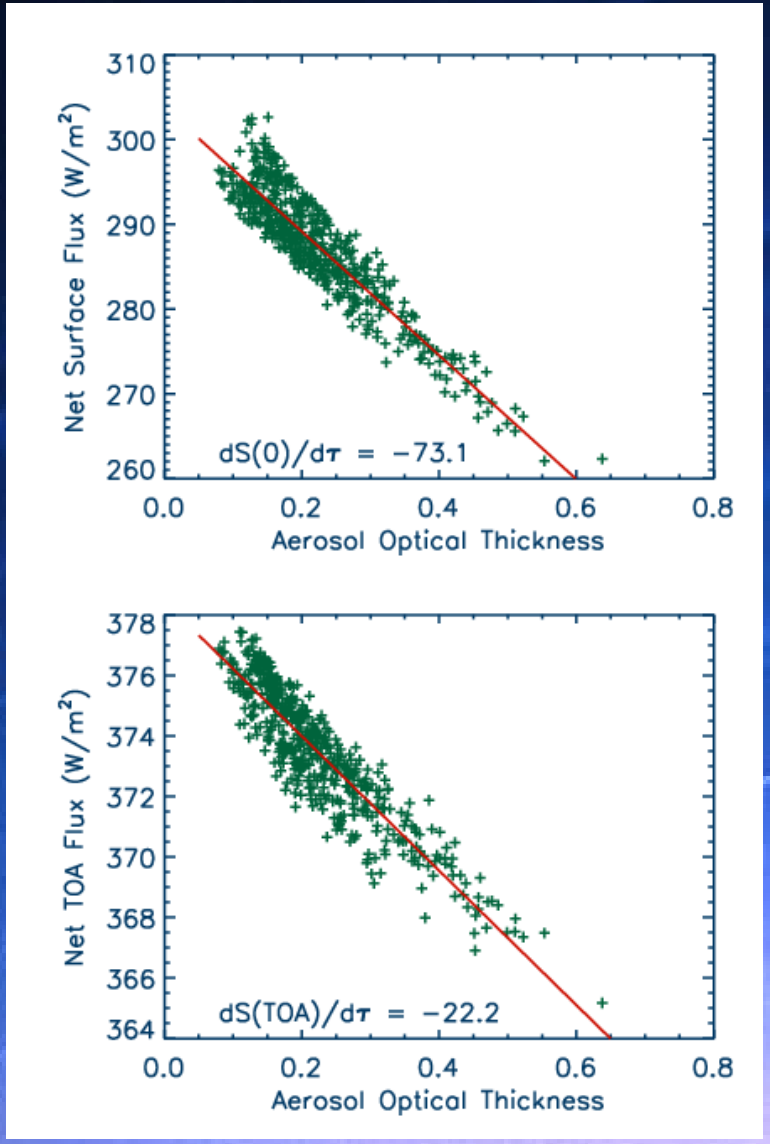
MATCH with MODIS Assimilation

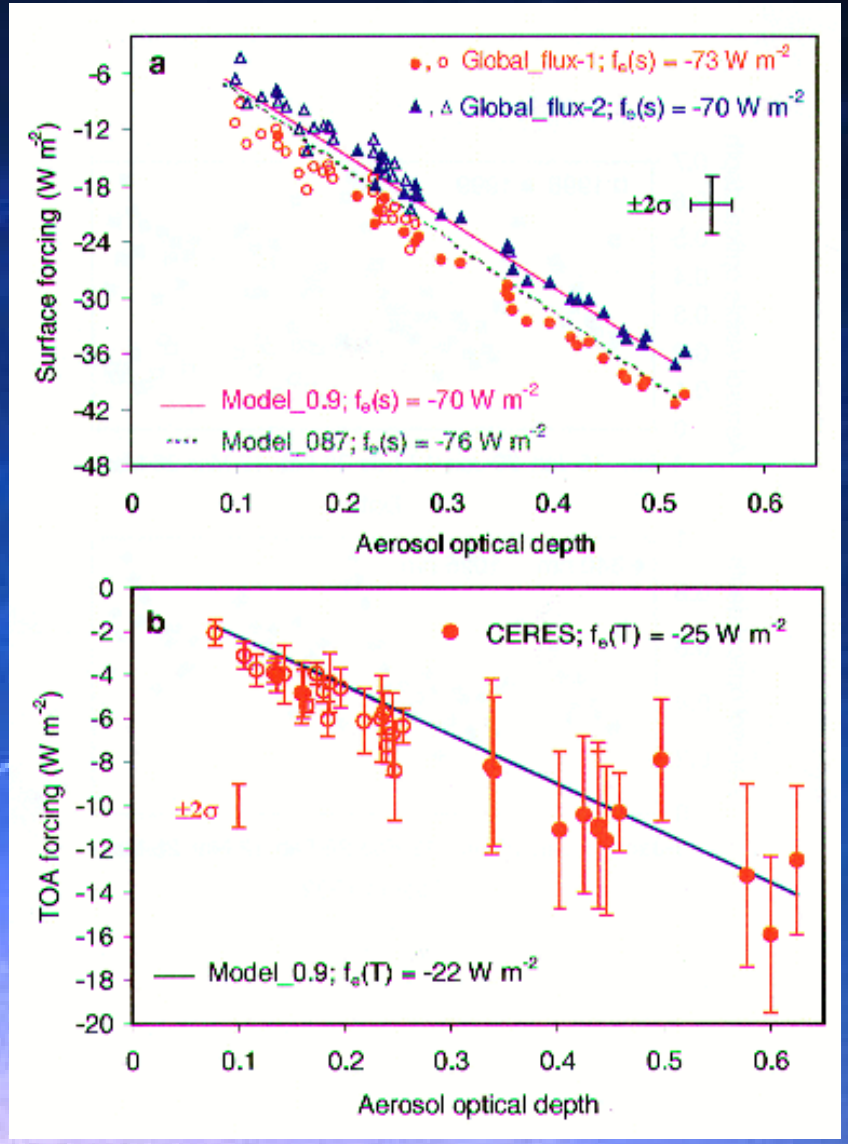
Assimilation Correction

Total Clear-sky Aerosol Forcing

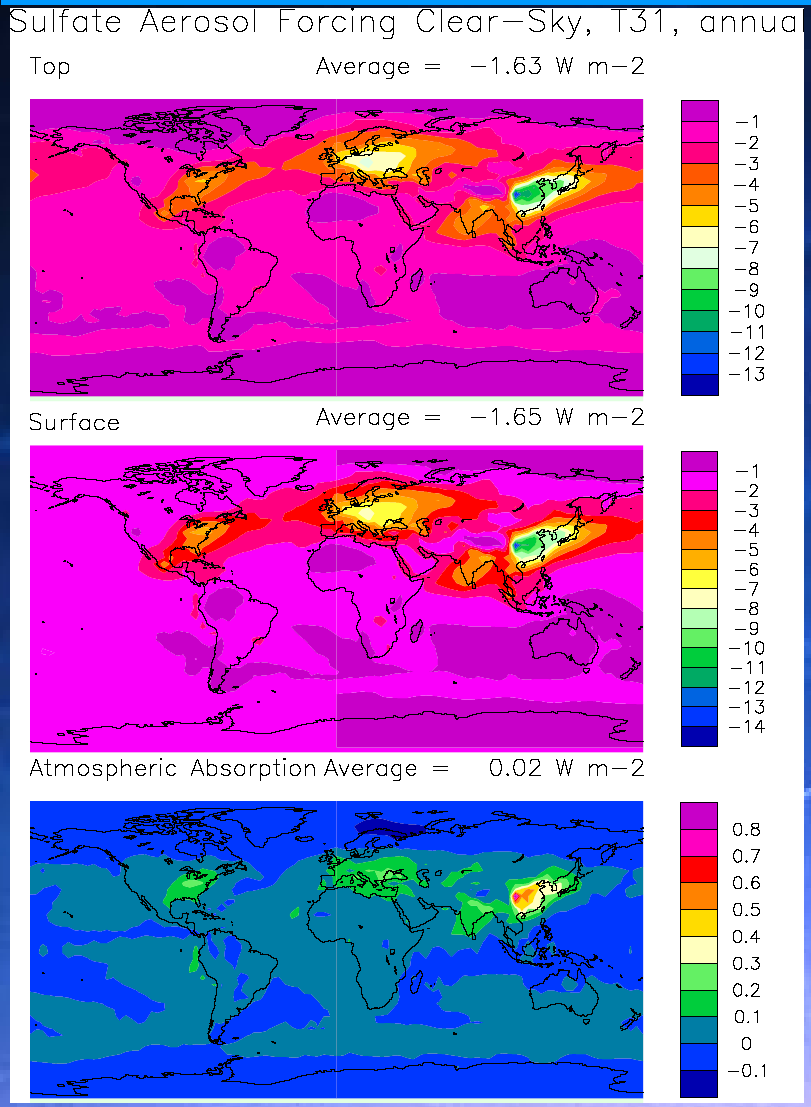


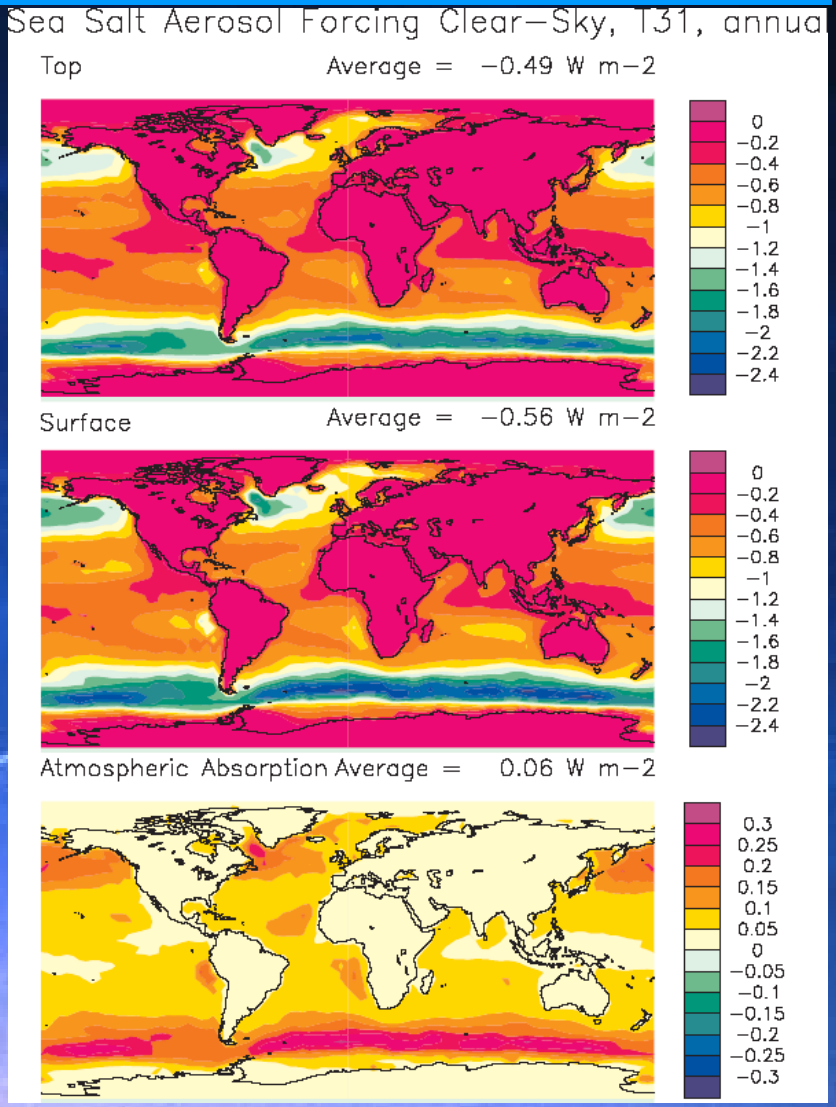
Relationship of optical depth and forcing



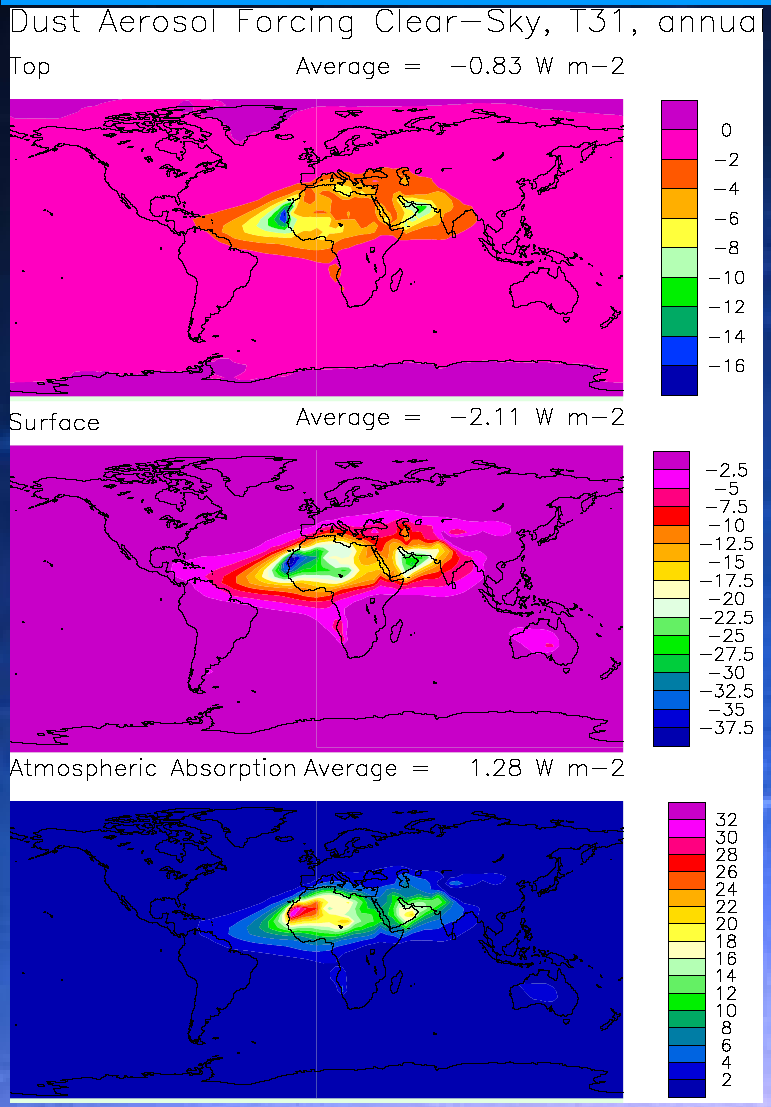


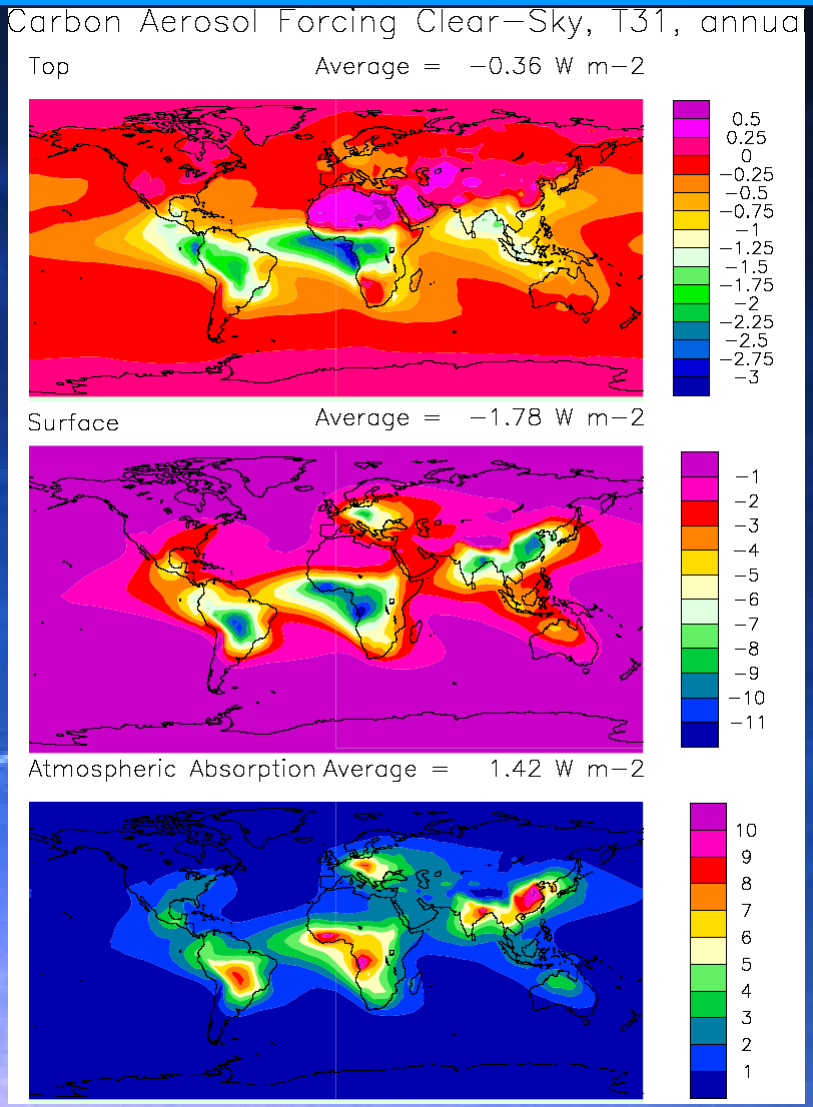
Clear-sky Forcing by Sulfate and Sea-Salt



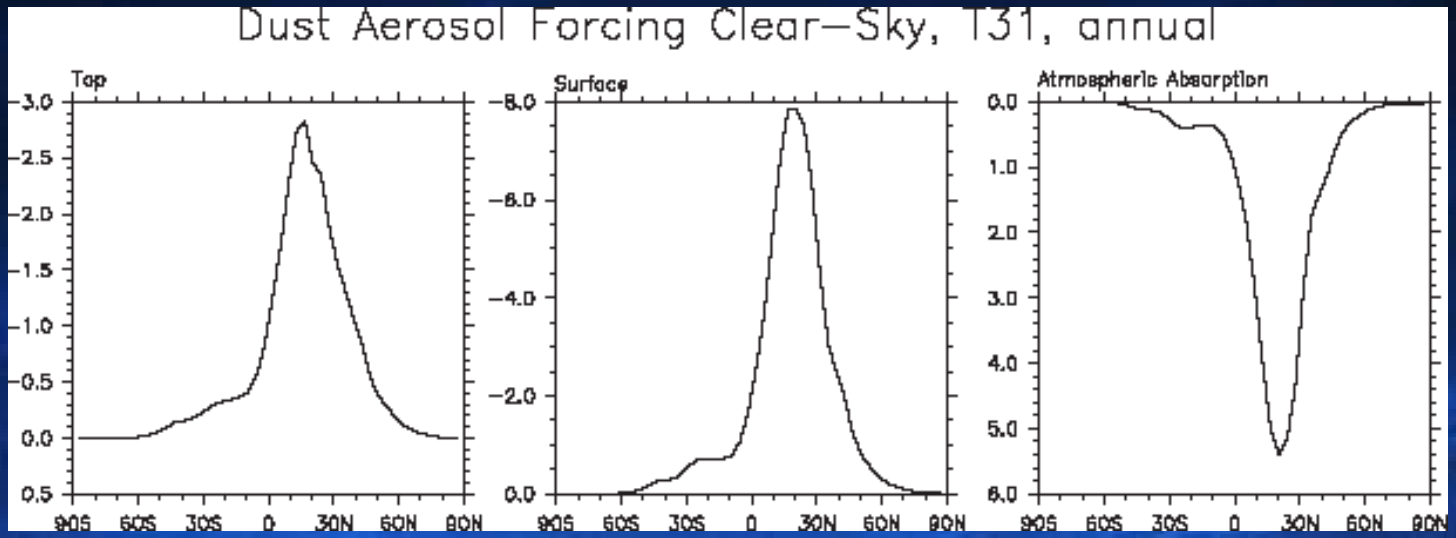


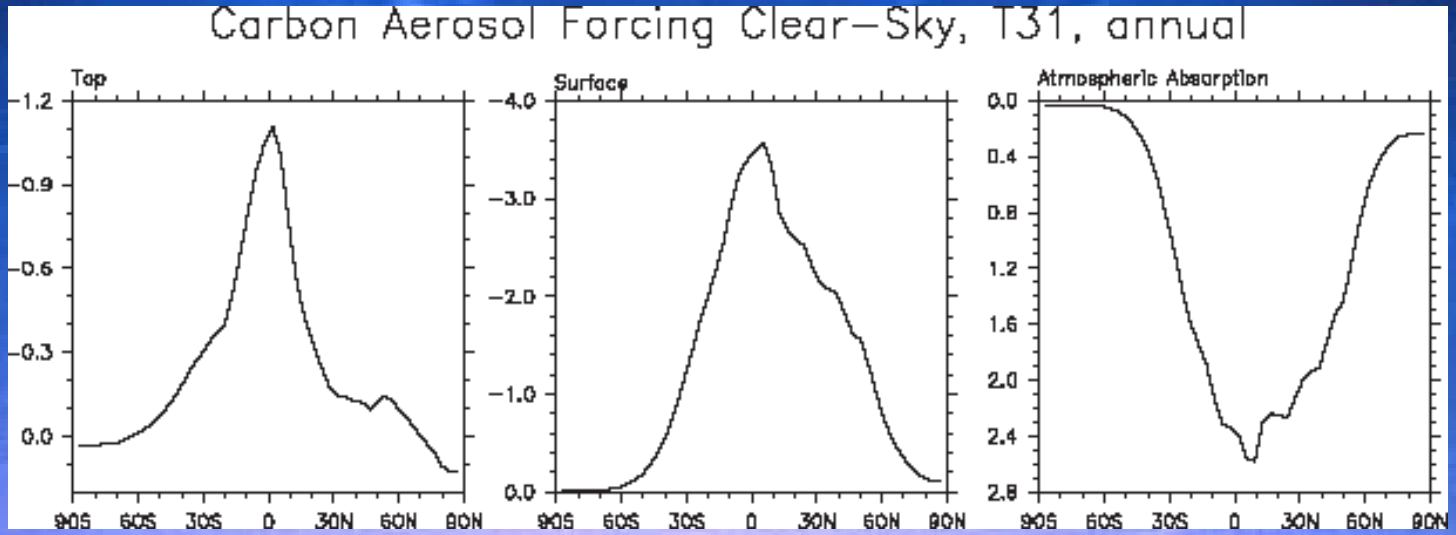
Clear-sky Forcing by Dust and Carbon





Meridional Distribution of Absorption





Summary of Shortwave Clear-sky Forcing

Surface	Units	Total	Sulfate	BC/OC	Dust	Sea salt
TOA	W/m^2	–3.45	–1.63	–0.36	–0.83	–0.49
	Percent	100	47	10	24	14
			Sulfate dominates TOA forcing.			
Surface	W/m^2	–6.25	–1.65	–1.78	–2.11	–0.56
	Percent	100	26	28	34	9
			No species dominates surface forcing.			
Atmosphere	W/m^2	+2.80	+0.02	+1.42	+1.28	+0.05
	Percent	100	1	51	46	2

BC/OC and dust are primary absorbers.

Method for Eliminating Absorption

- Aerosol forcing *(single-scattering approximation, black surface)*:

$$\Delta R = -\omega b \tau = -b \tau_s$$

ω = Single scattering albedo

τ = Extinction optical depth

τ_s = Scattering optical depth

b = Backscatter fraction

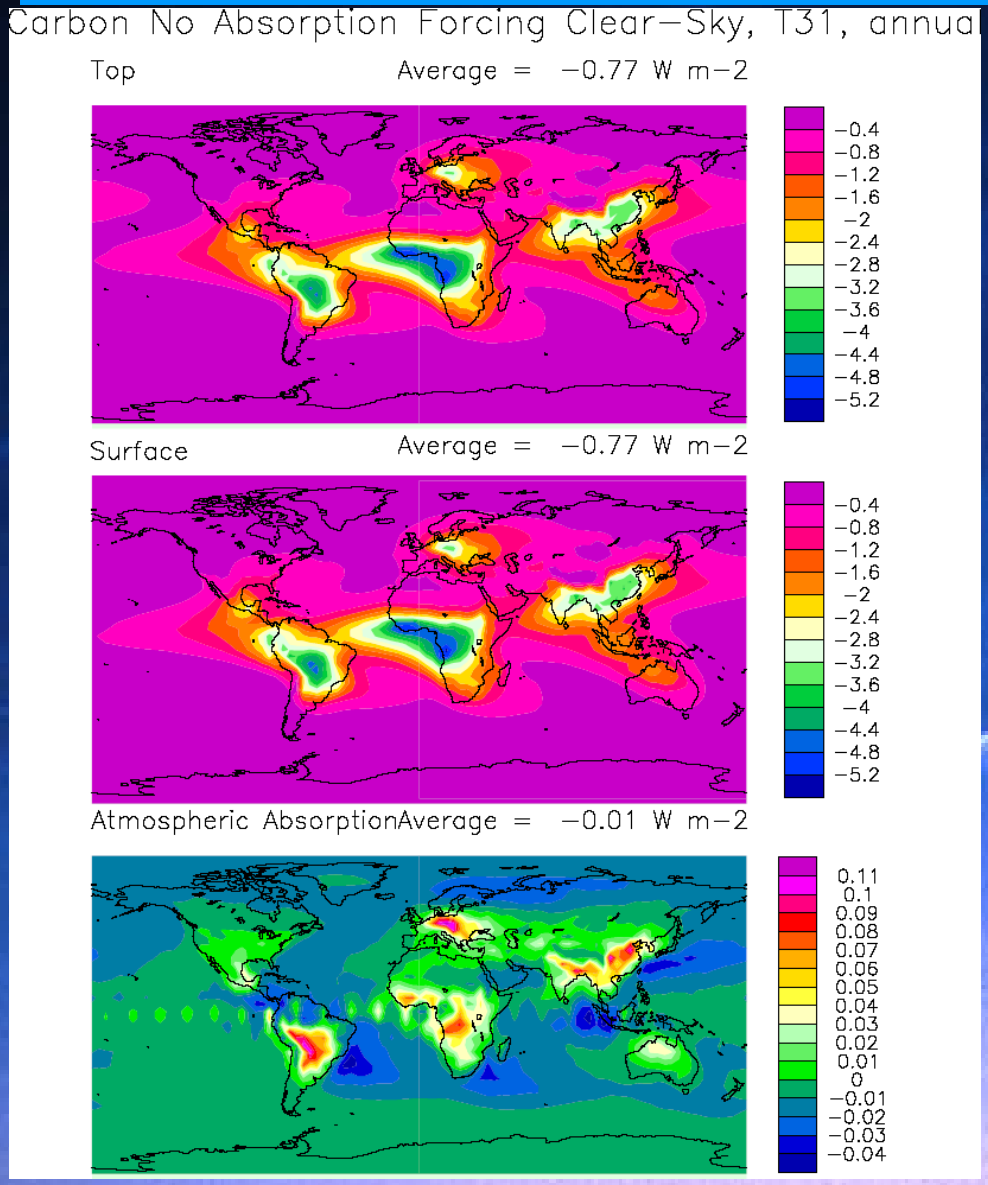
- Method for eliminating absorption:

$$\tau \rightarrow \tau_s$$

$$\omega \rightarrow 1$$

- To first order, forcing ΔR is preserved.

Clear-sky Forcing by Carbon, No Absorption



Surface	BC/OC	BC/OC No Abs
TOA	–0.36	–0.77
Surface	–1.78	–0.77
Atmosphere	+1.42	–0.01

Forcing with surface reflection ΔR_S :

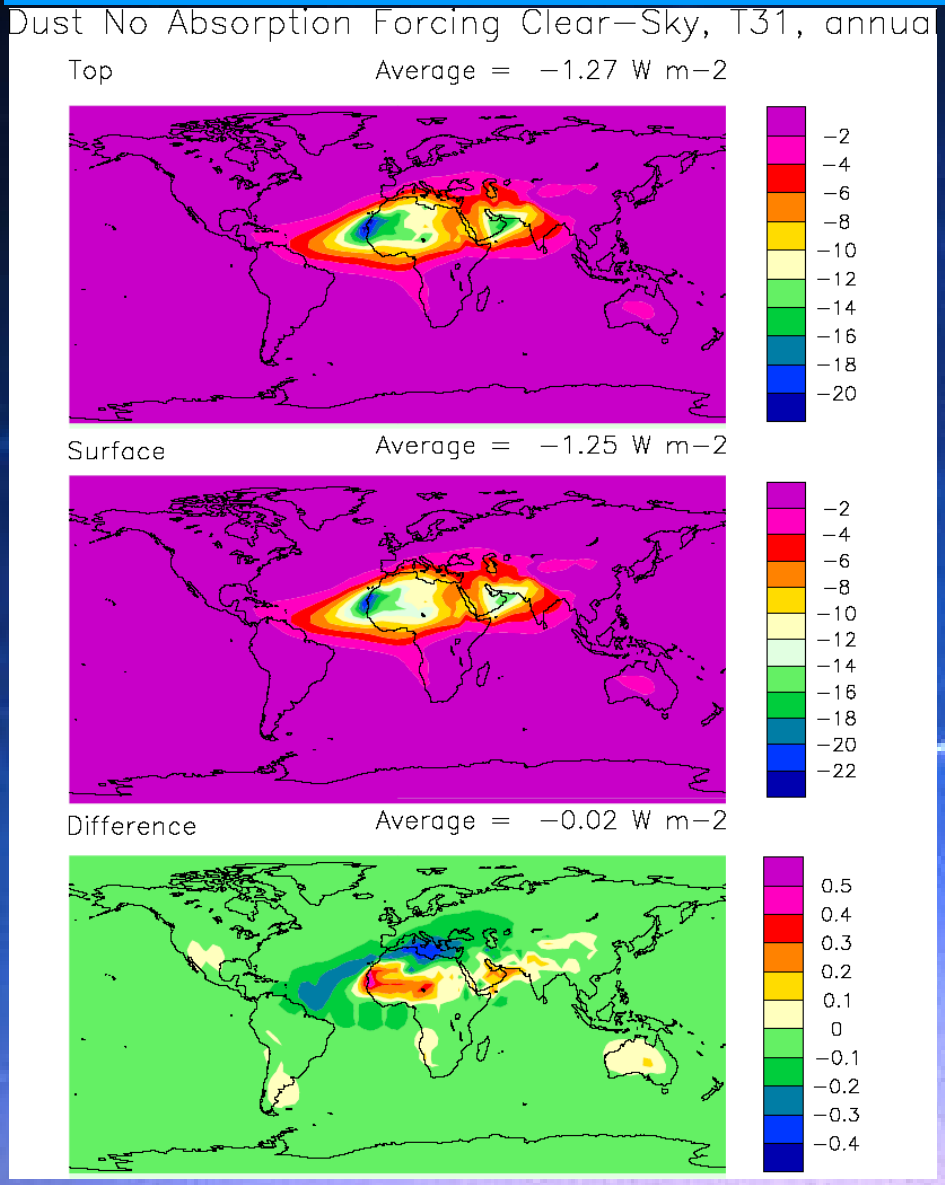
$$\Delta R' = (1 - R_S)^2 \Delta R + 2R_S \Delta A$$

$$\Delta A = \text{Aerosol Absorption}$$

When absorption $\Delta A \rightarrow 0$,

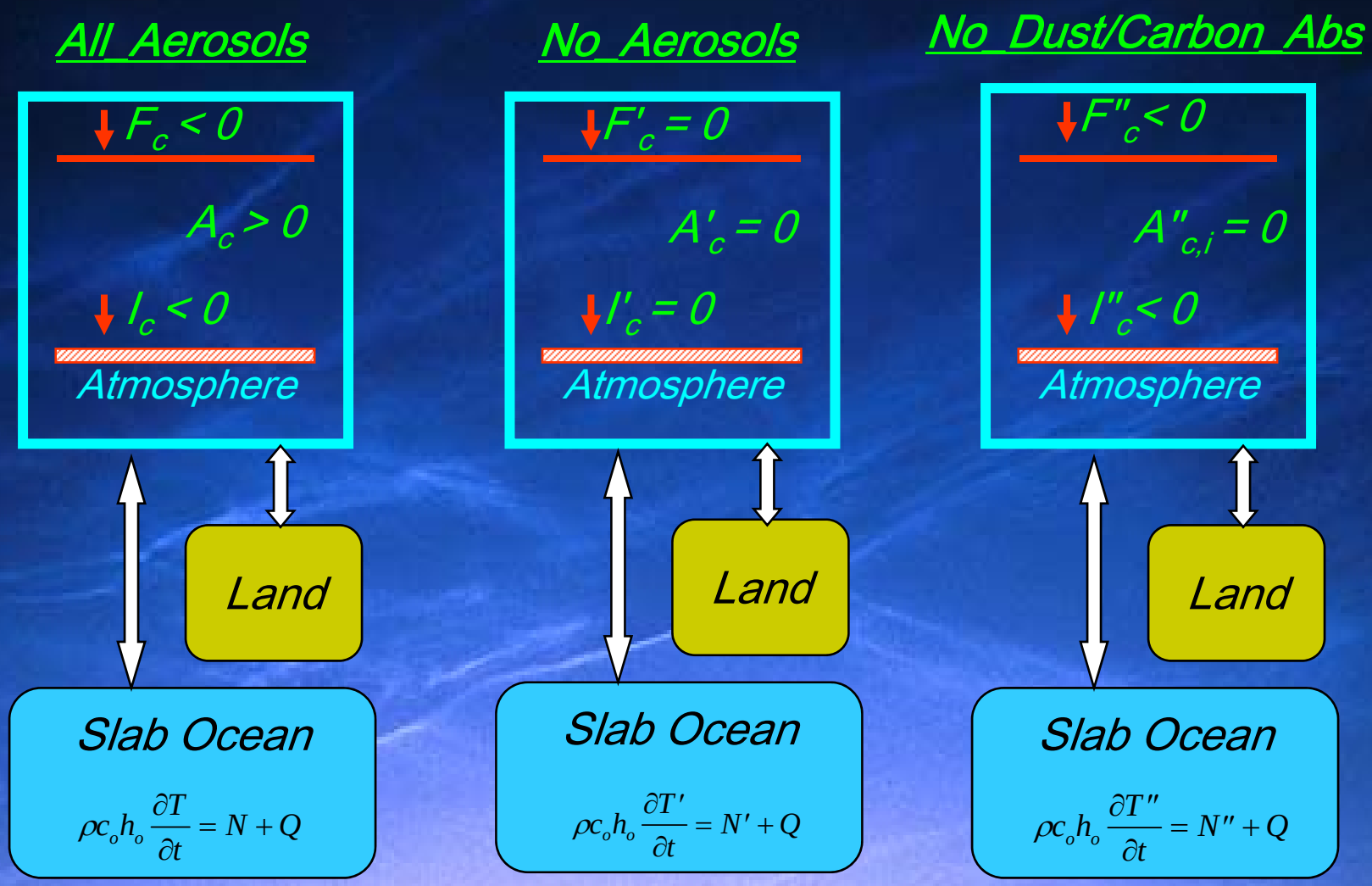
$$\Delta R'_{noabs} = (1 - R_S)^2 \Delta R$$
$$< \Delta R'$$

Clear-sky Forcing by Dust, No Absorption

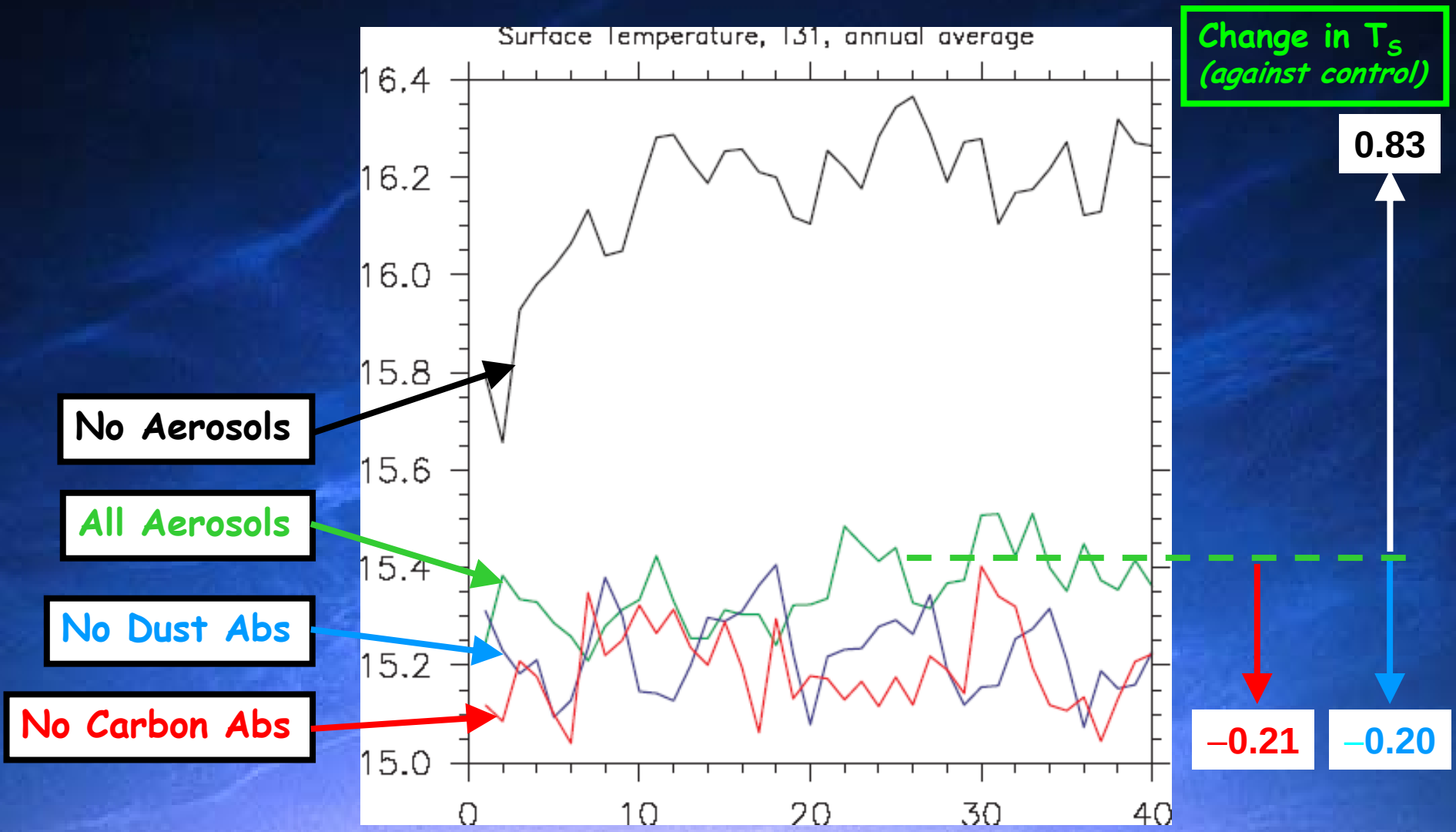


Surface	DUST	DUST No Abs
TOA	–0.83	–1.27
Surface	–2.11	–1.25
Atmosphere	+1.28	–0.02

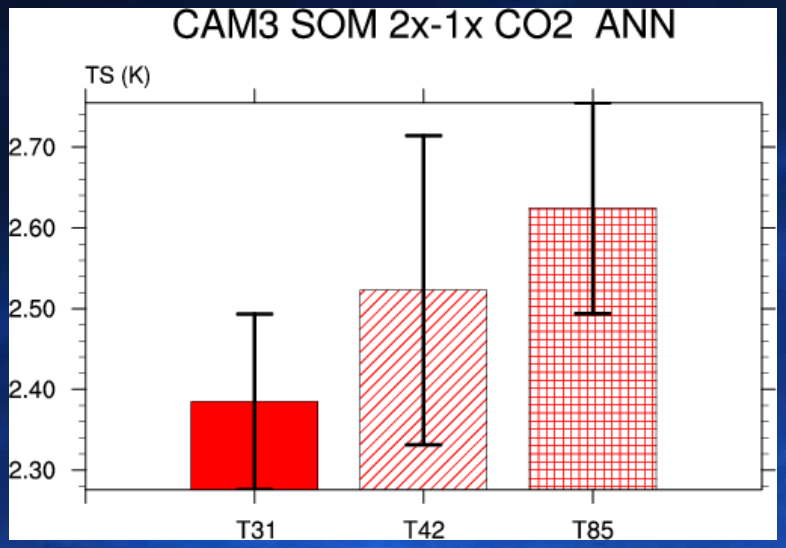
Slab Ocean Experiments

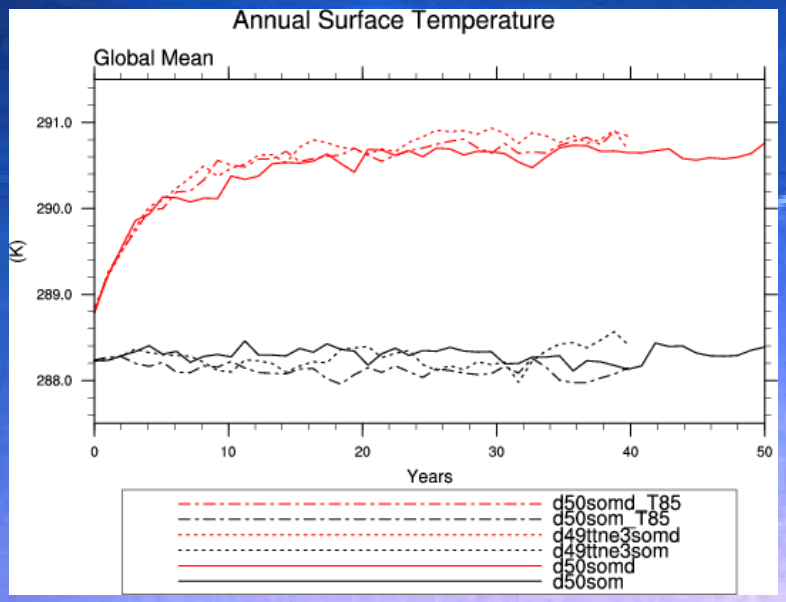


Response of CAM+SOM to Aerosols



Relationship of $\Delta T_{s,a}$ to Aerosol Effects





For $2xCO_2$:

$$\Delta T_s = \lambda \, \Delta F$$

$\Delta T_s = 2.37 +/- 0.58$ K
$\Delta F = 3.7$ Wm^{-2}

$\Rightarrow \lambda_{CO2} = 0.64 +/- 0.16$ $K/(Wm^{-2})$

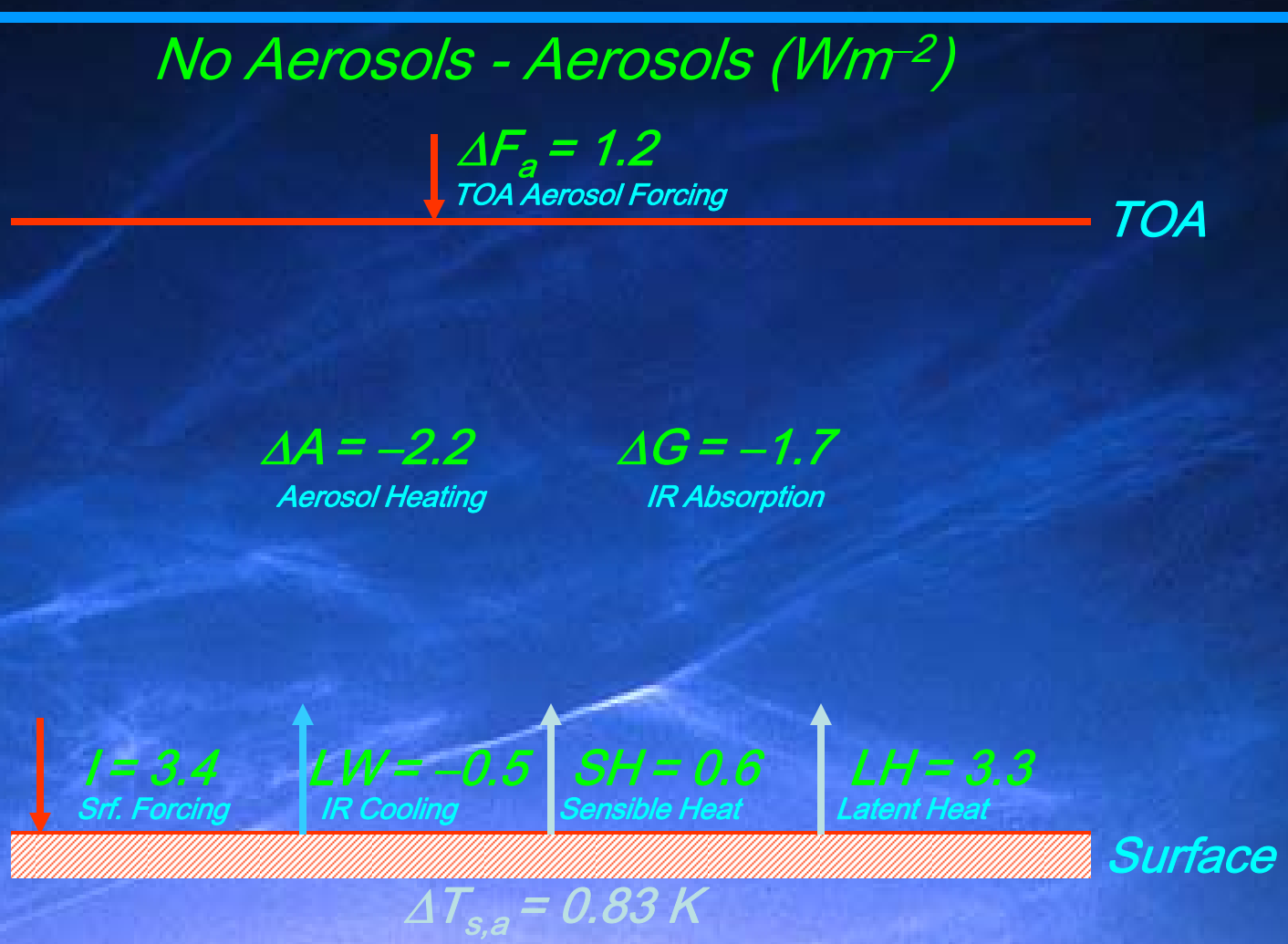
For aerosols:

$\Delta T_{s,a} = -0.81 +/- 0.29$ K
$\Delta F_a = -1.46$ Wm^{-2}

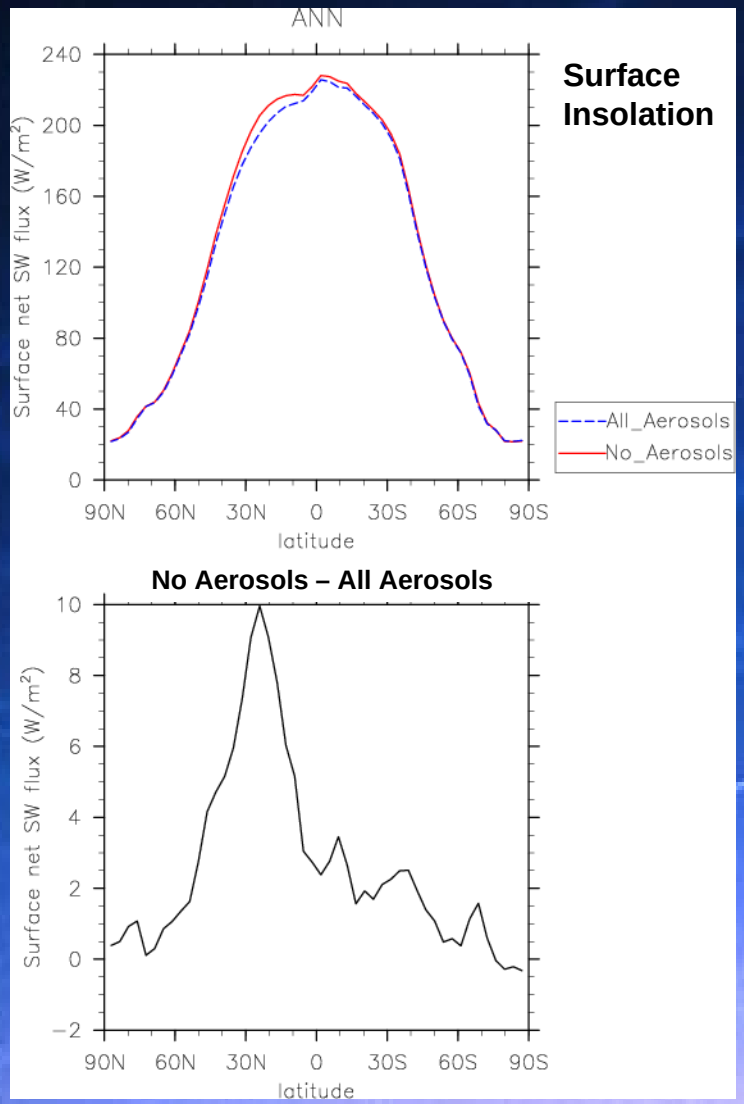
$\Rightarrow \lambda_a = 0.56 +/- 0.2$ $K/(Wm^{-2})$

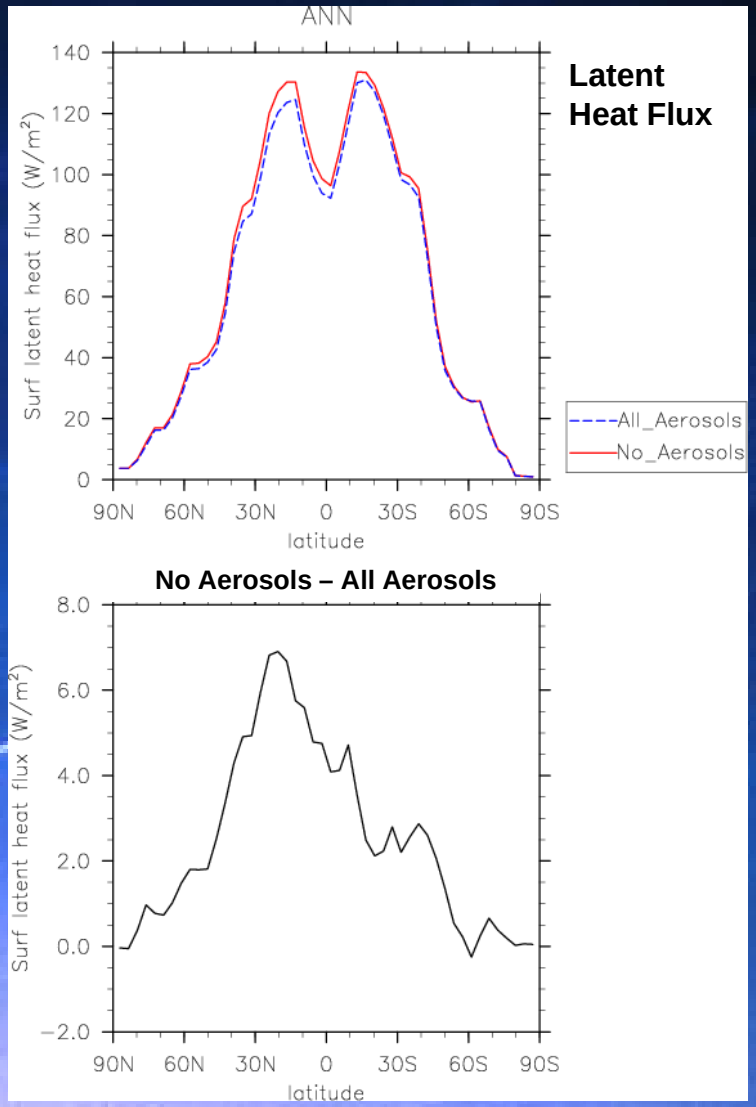
Efficacy $r = \lambda_a / \lambda_{CO2} = 0.87 +/- 0.38$

Effect of Aerosols on Energy Budgets

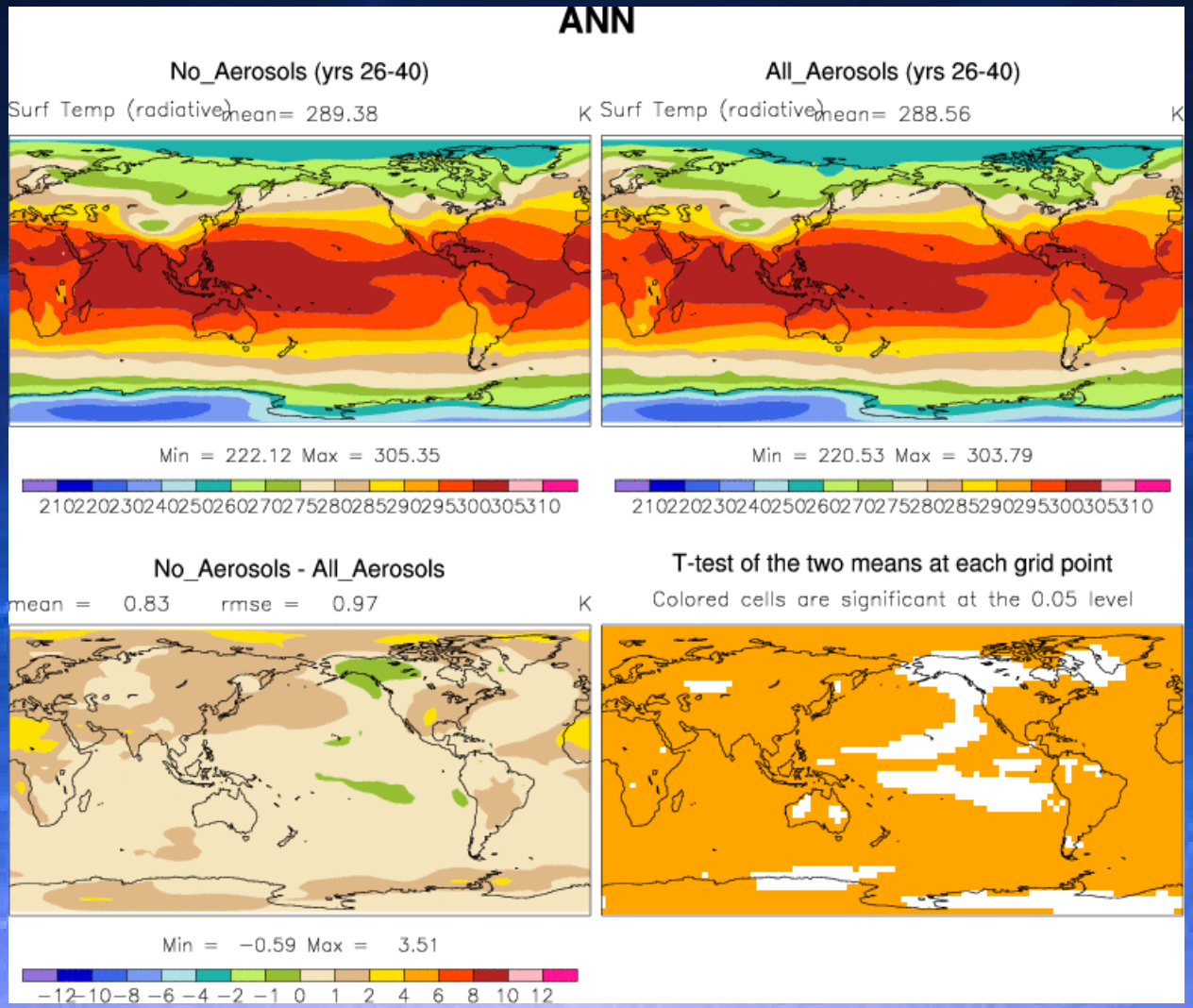


Aerosols reduce the surface latent heat flux

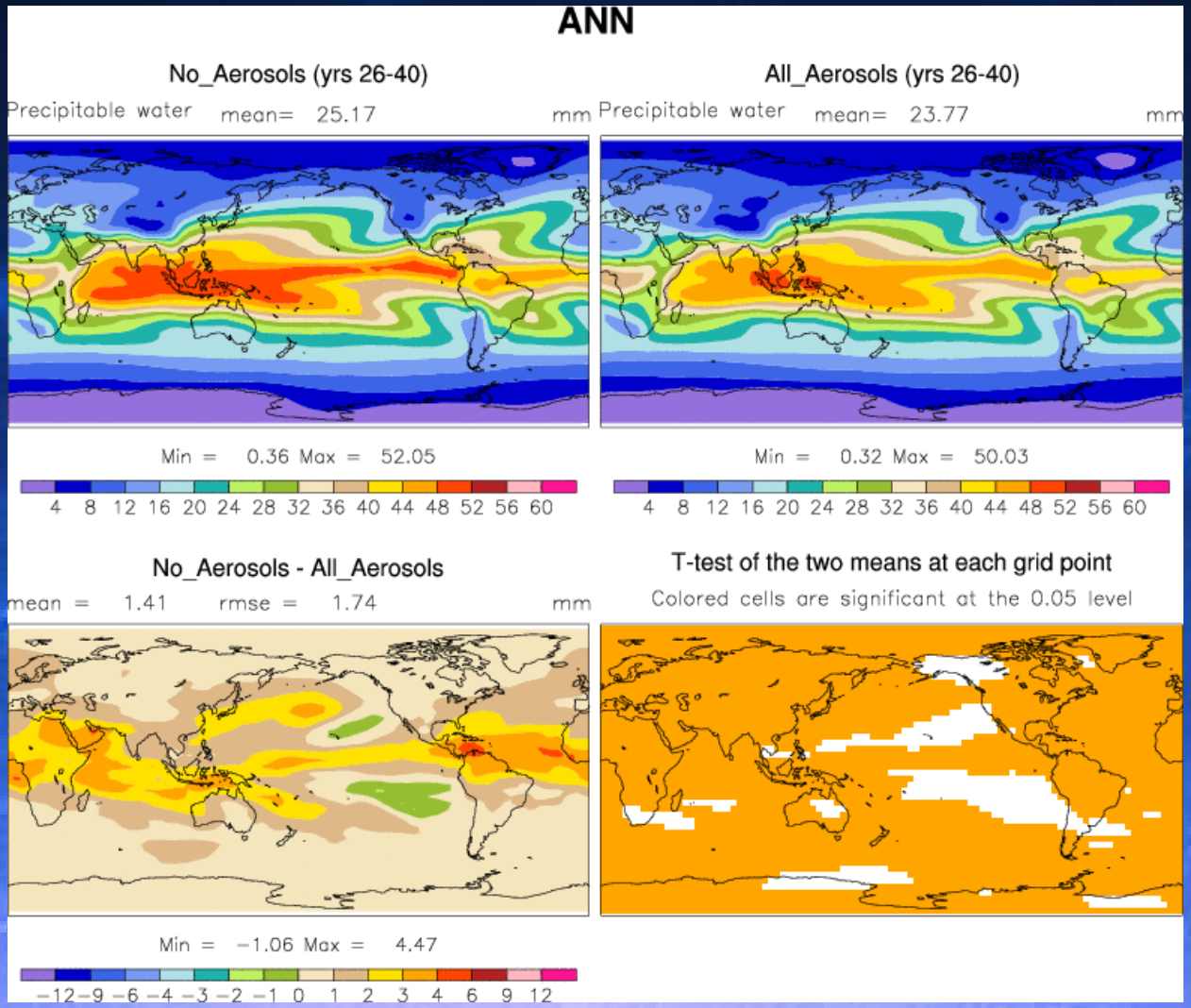




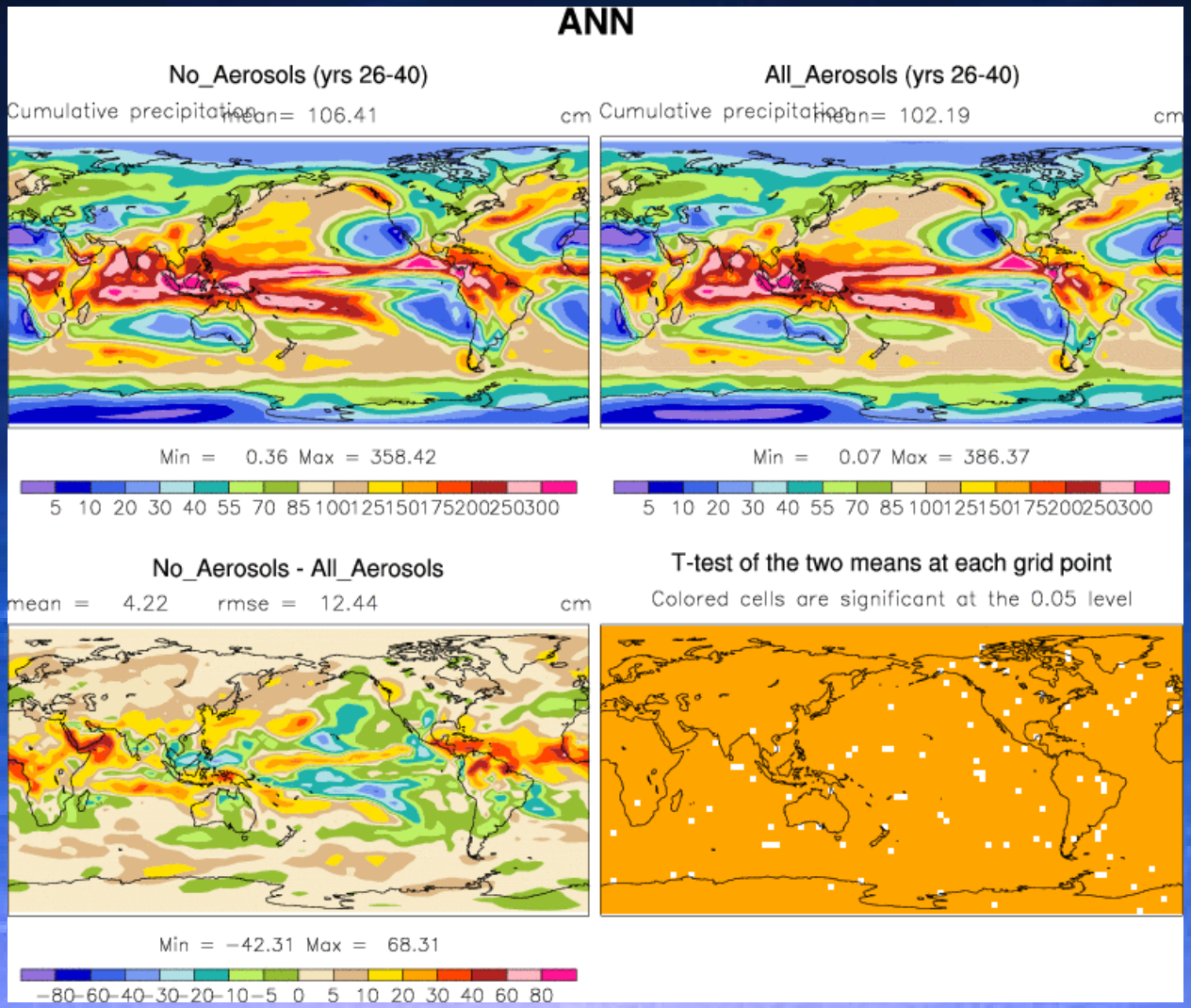
Aerosols reduce surface temperatures



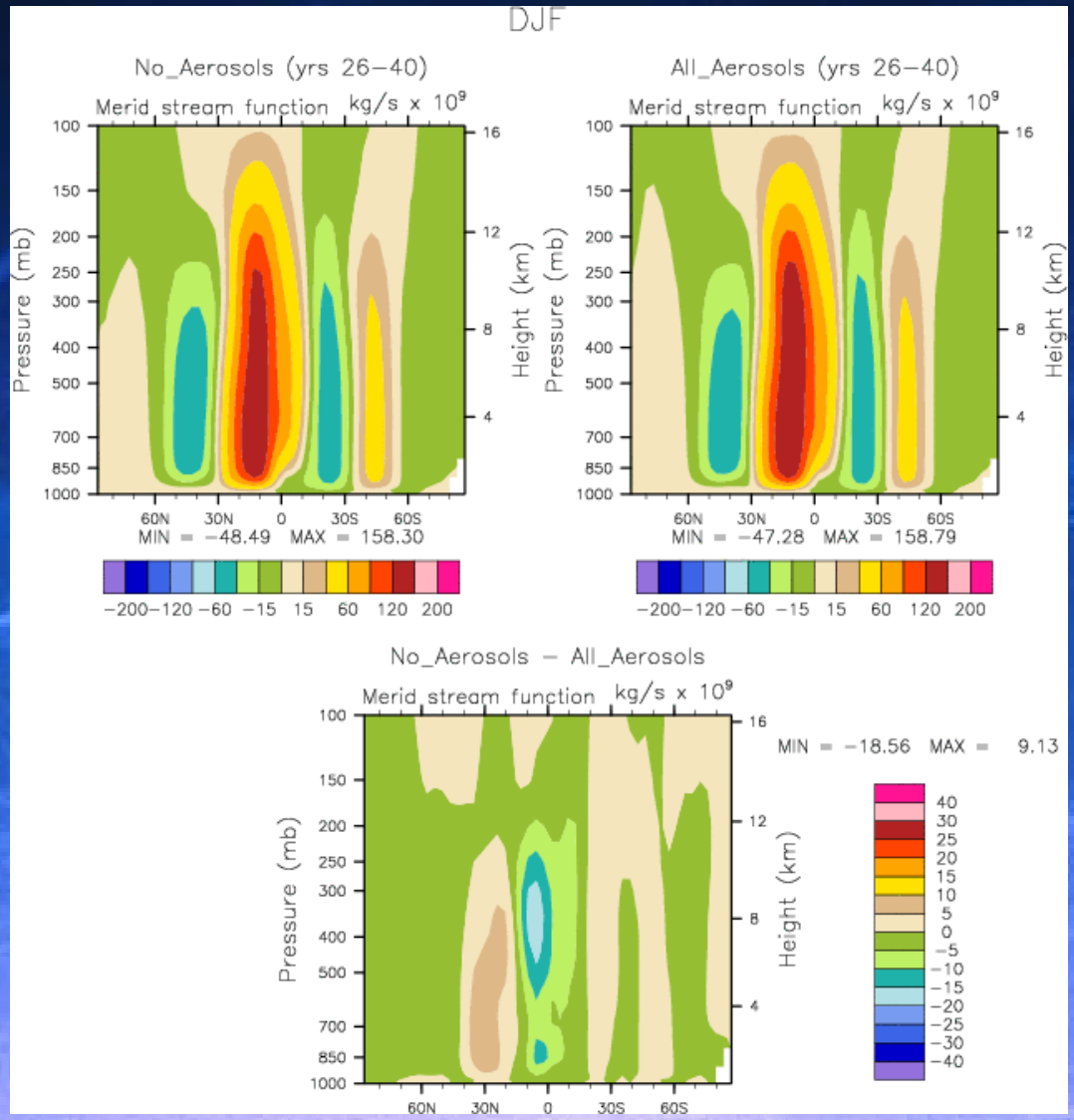
Aerosols enhance tropospheric moisture



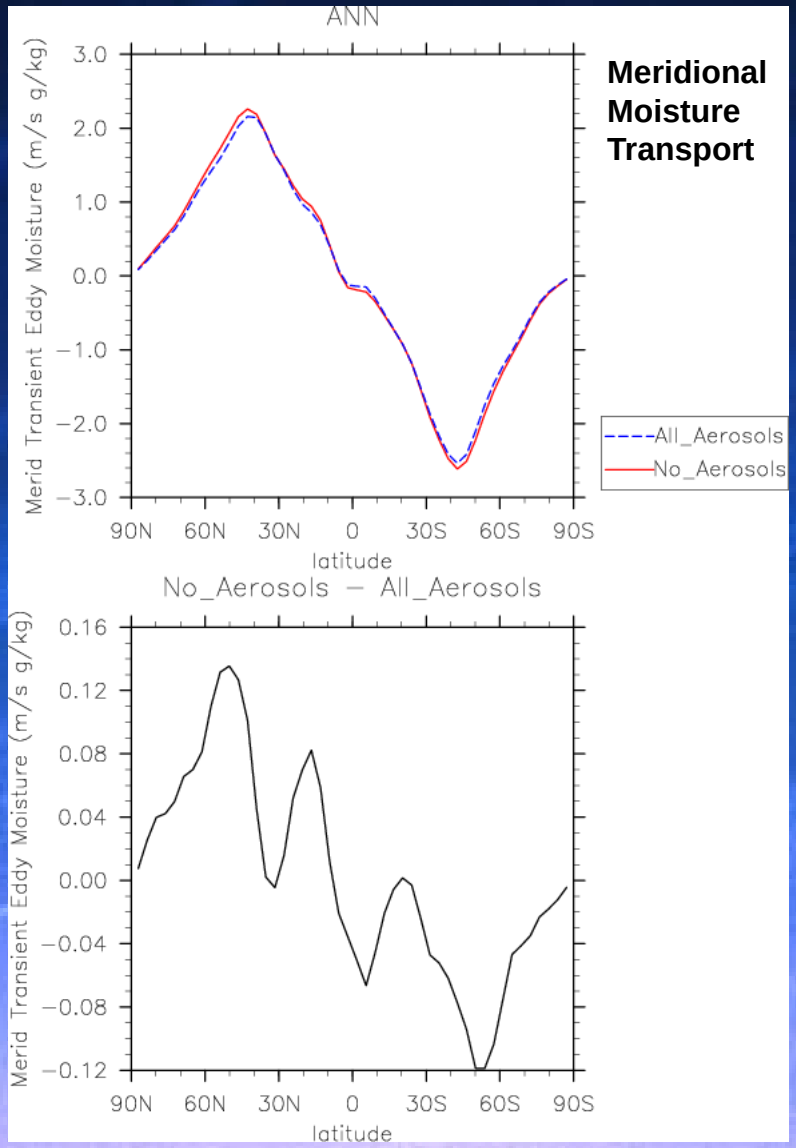
Aerosols reduce cumulative precipitation



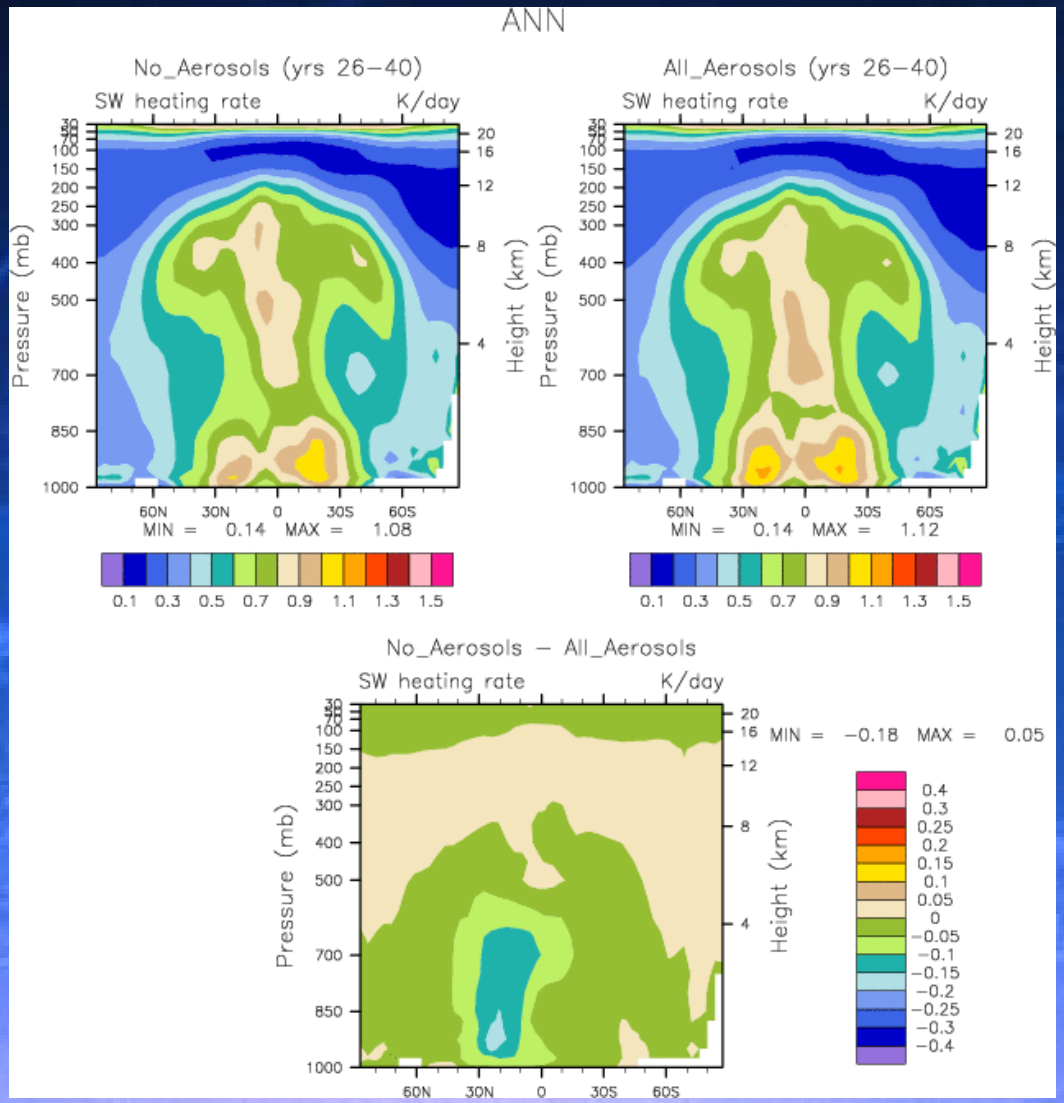
Aerosols reduce the Hadley circulation



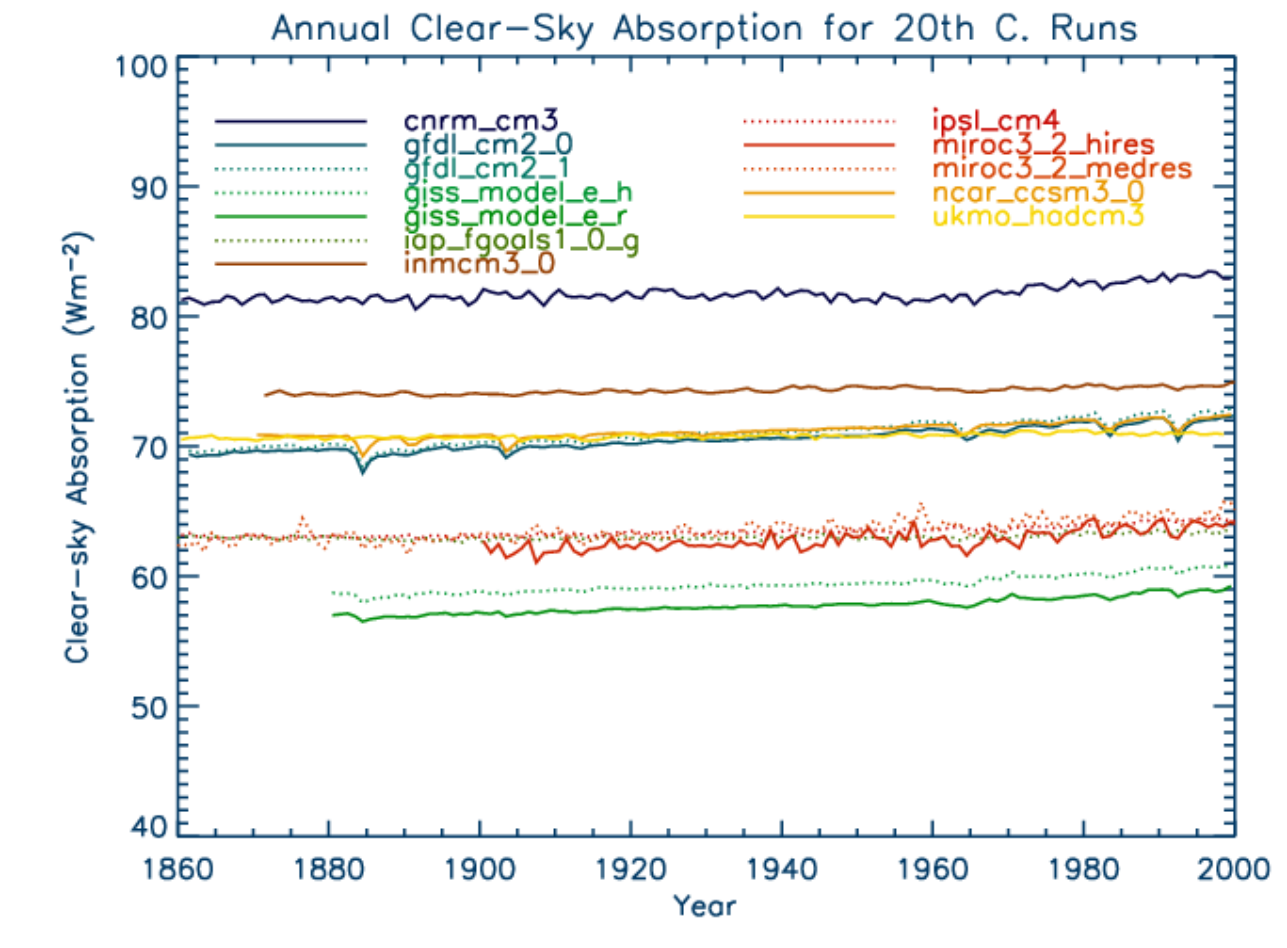
Aerosols slow the hydrological cycle



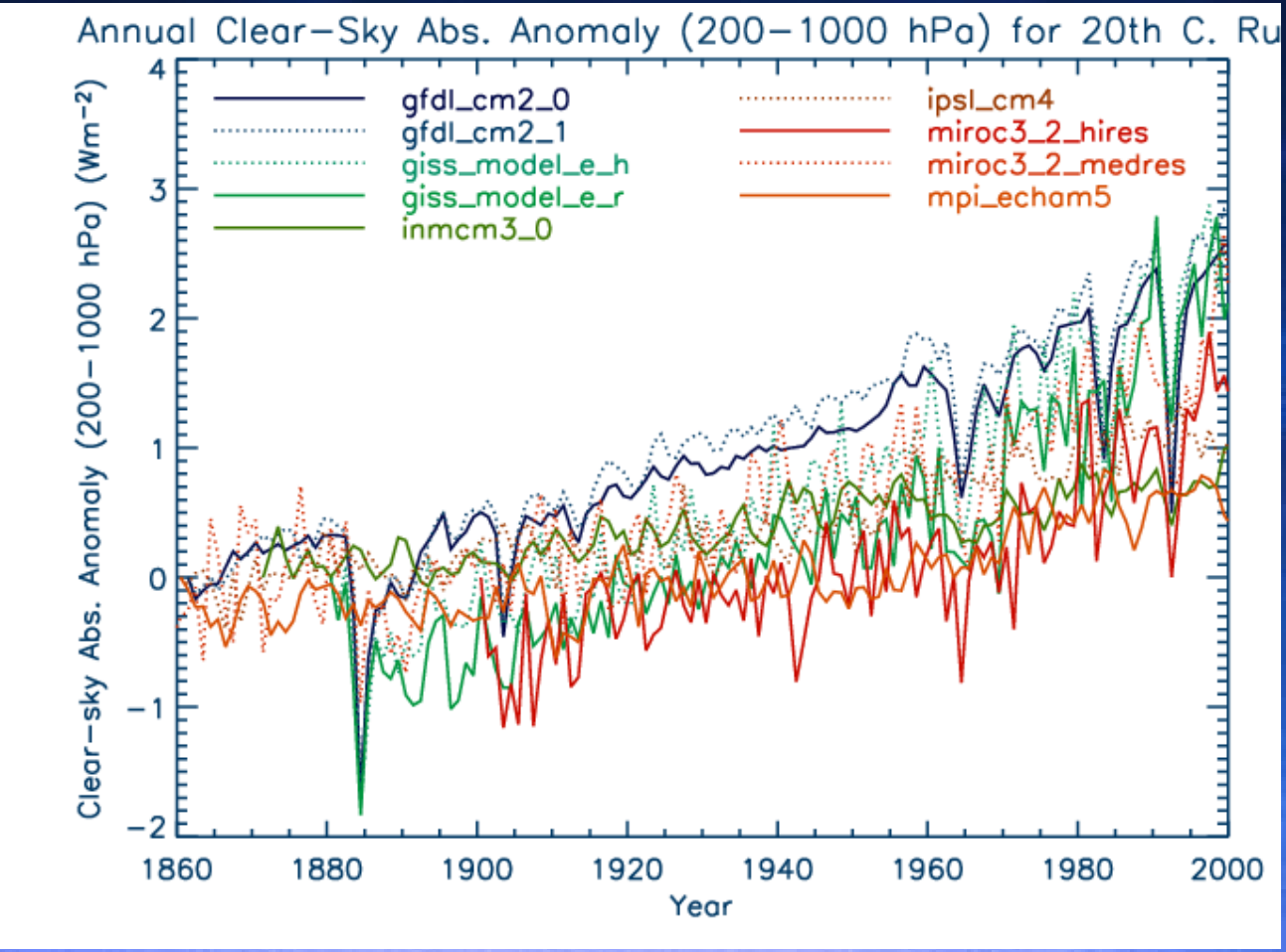
Heating by absorption in lower troposphere



Diversity of Absorption in AR4 Models



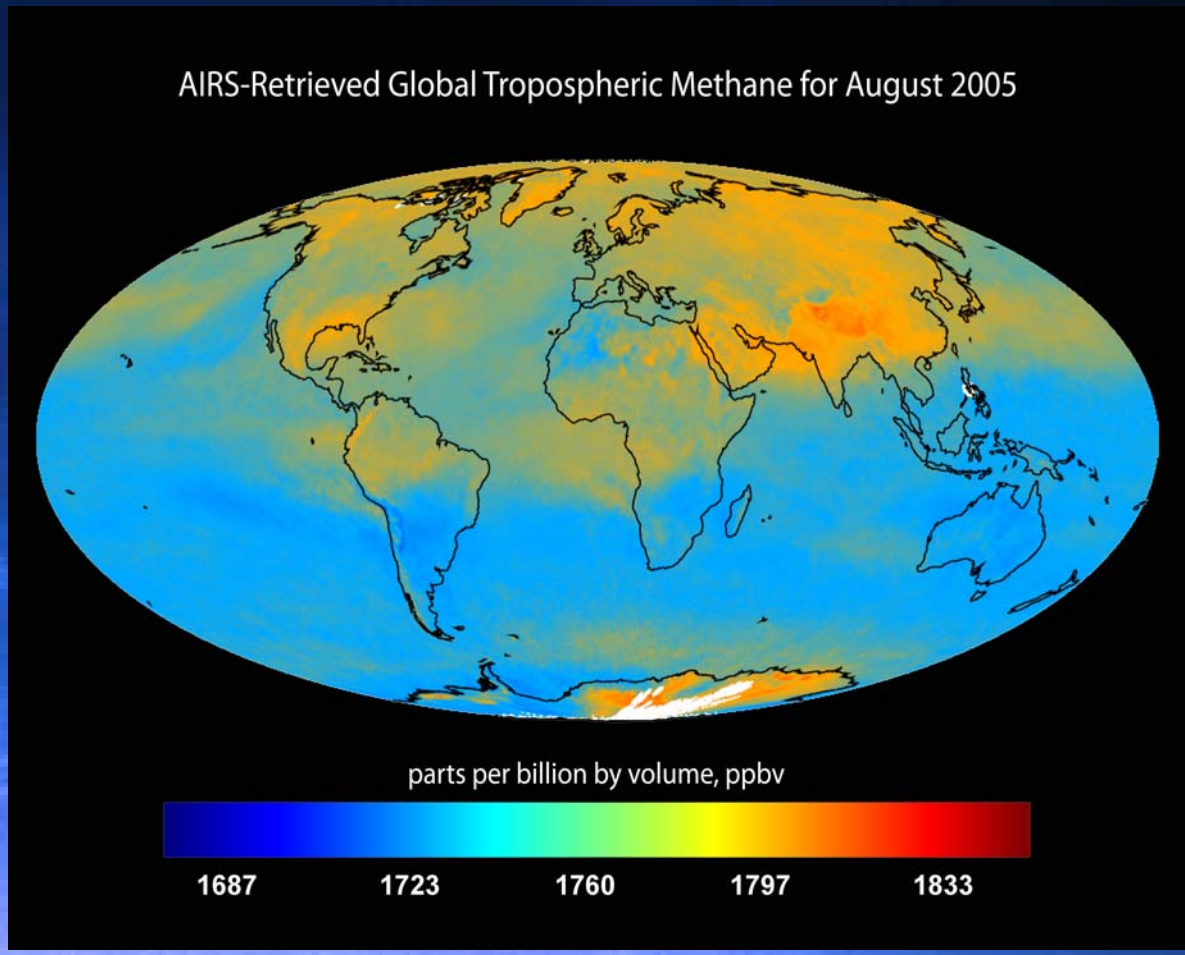
Upward trend in atmospheric absorption?



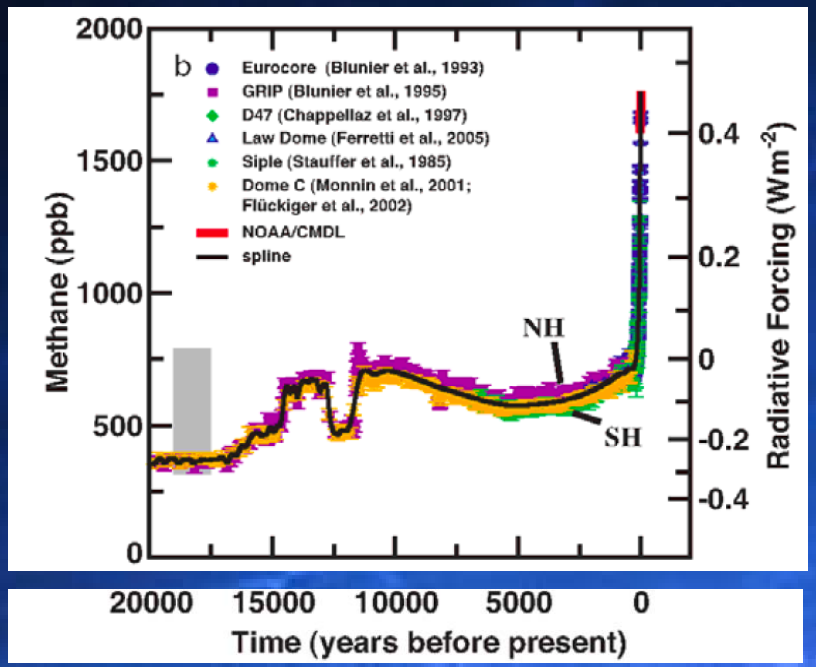
Example of a missing absorber: Methane

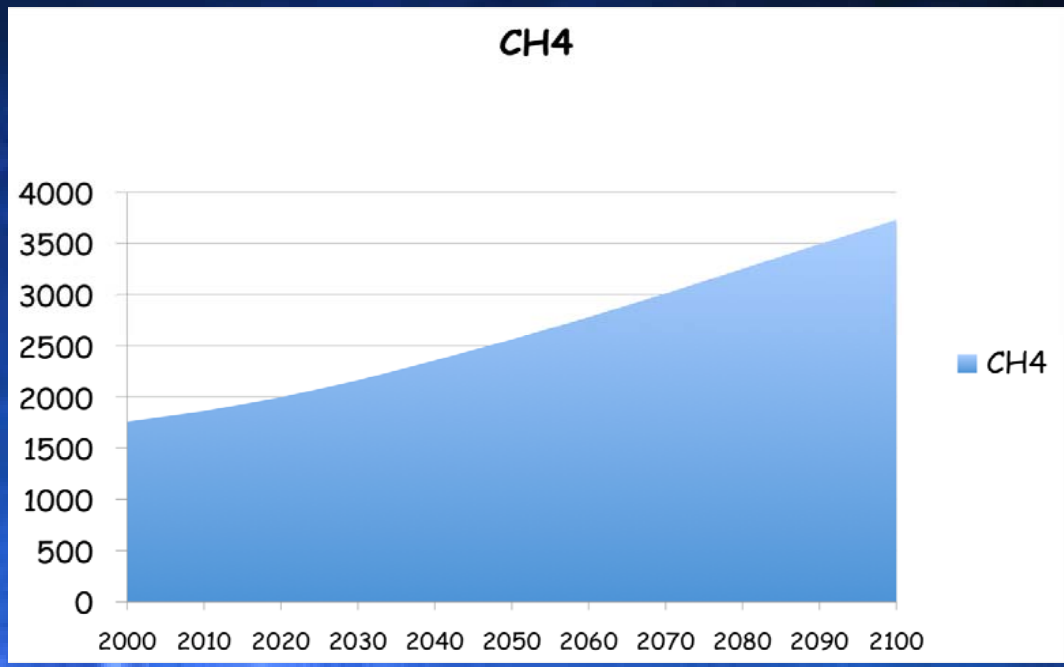
Analysis:

- Evidence for missing methane forcing in climate models
- Benchmark calculations for the effects of methane on sunlight
- Climate model simulations with absorption of sunlight by methane



Changes in methane concentrations

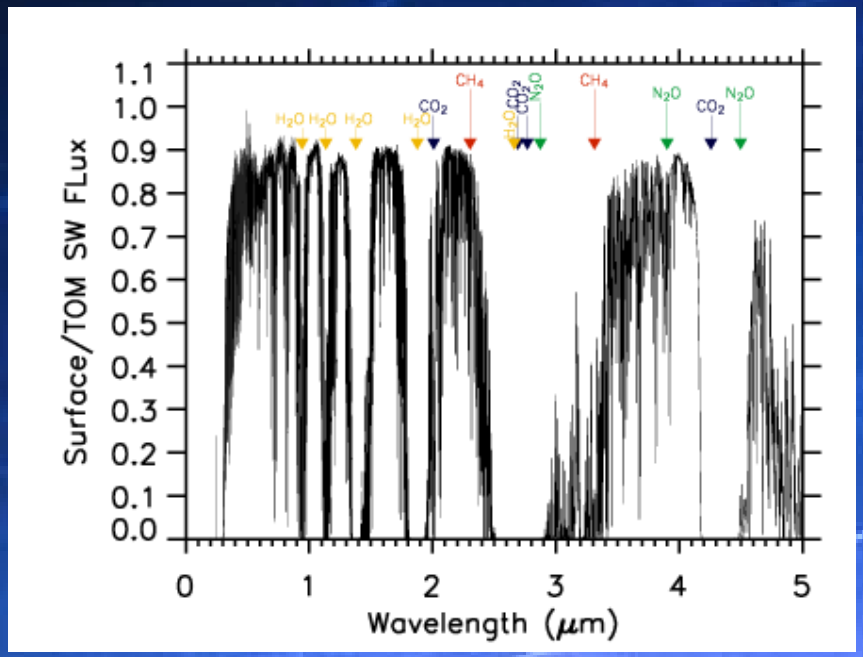




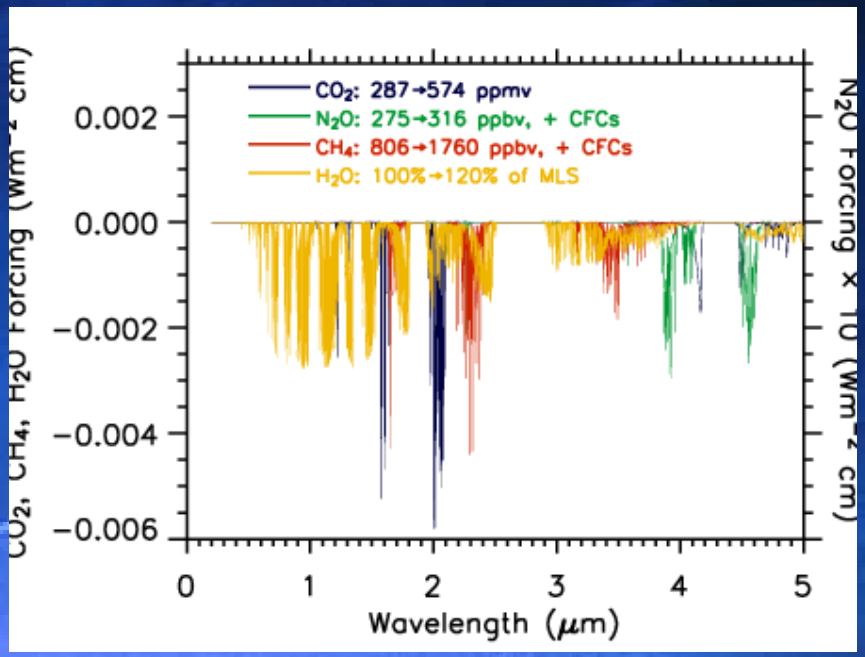
Methane concentrations may quadruple by the end of the 21st century.

Shortwave radiative forcing at the surface

Transmission



Forcing

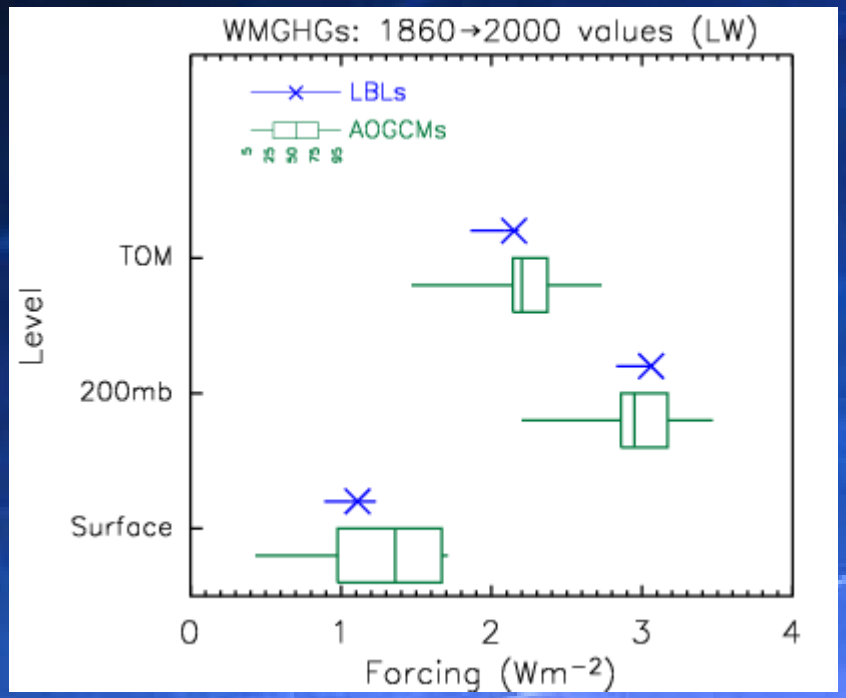


Shortwave forcings decrease the amount of sunlight reaching the surface.

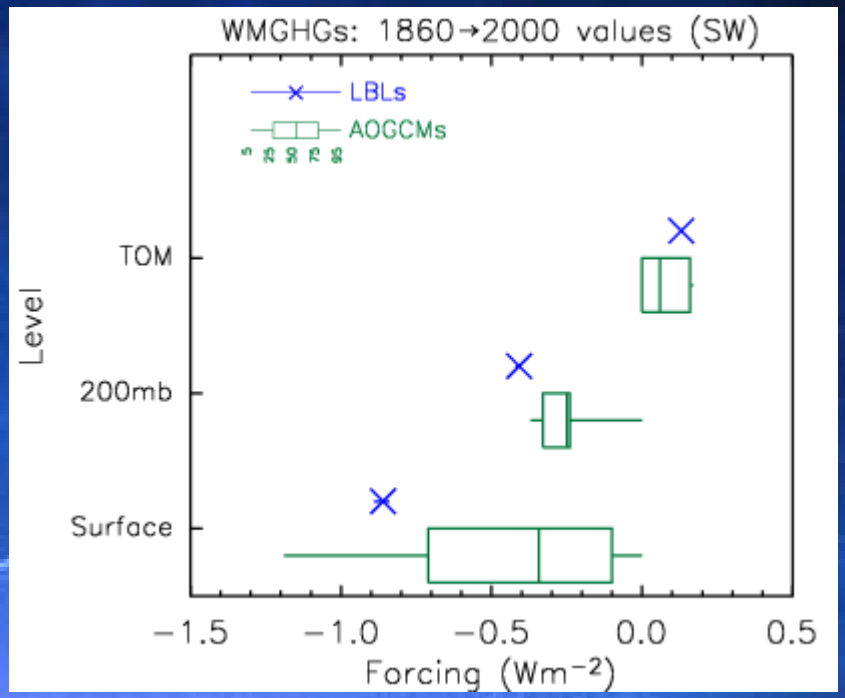
Collins et al, 2006

AOGCM forcing by historical increase in GHGs

Longwave



Shortwave

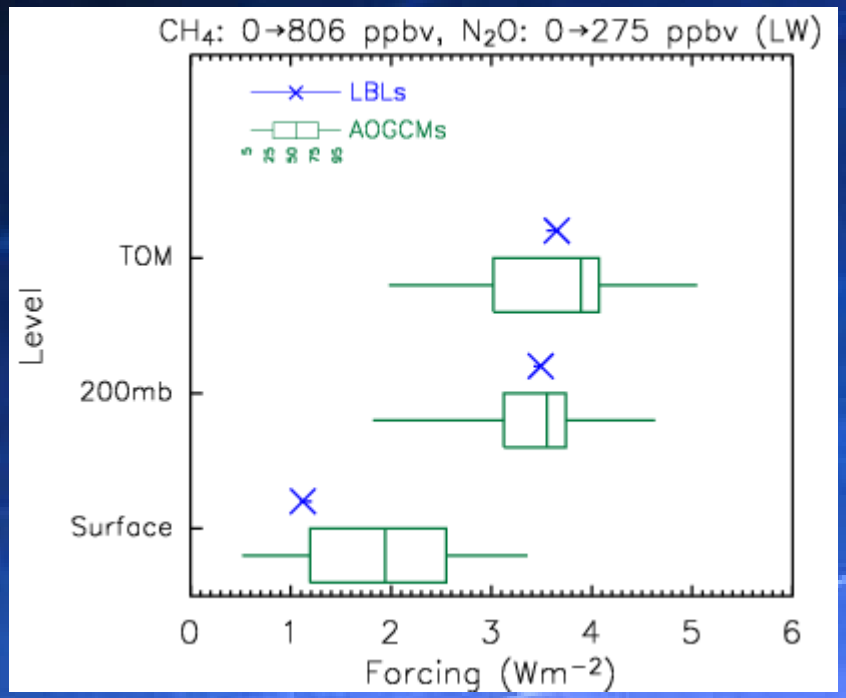


Longwave: None of the differences are statistically significant.
Shortwave: All of the differences are statistically significant.

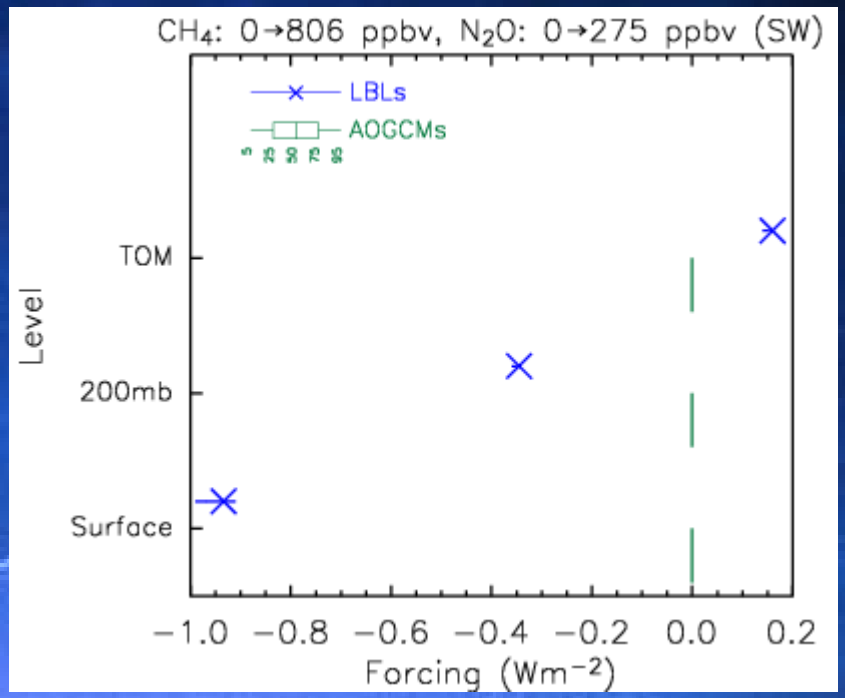
Collins et al, 2006

AOGCM forcing by methane and nitrous oxide

Longwave



Shortwave

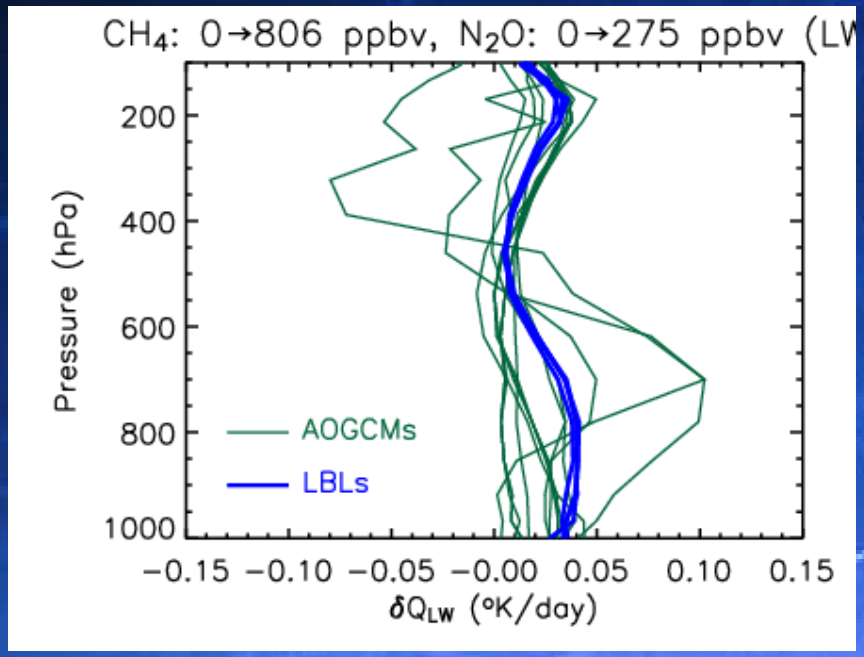


Longwave: The overestimation of surface forcing is statistically significant.
Shortwave: None of the codes treat the effects of CH4 and N2O.

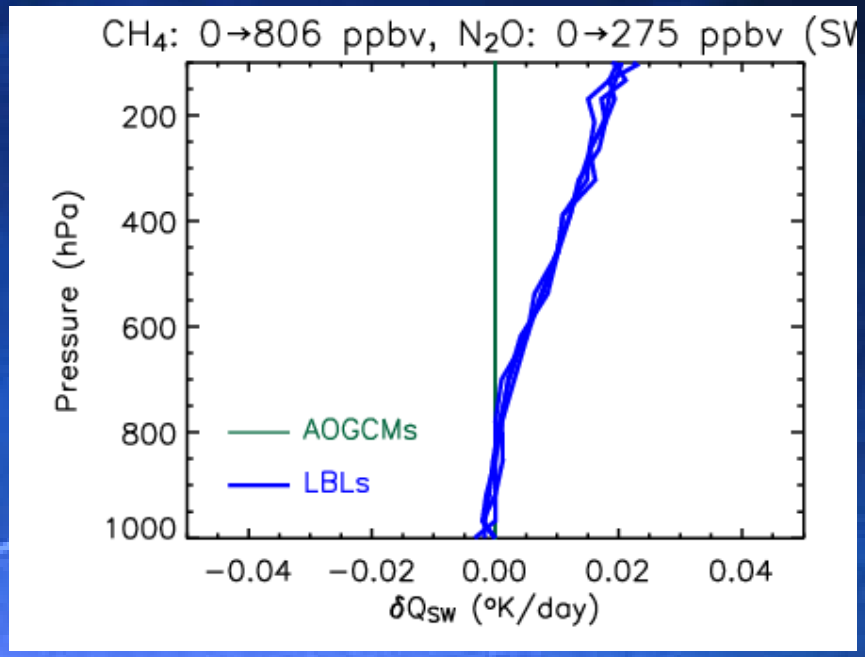
Collins et al, 2006

AOGCM change in heating rates by CH_4 and N_2O

Longwave



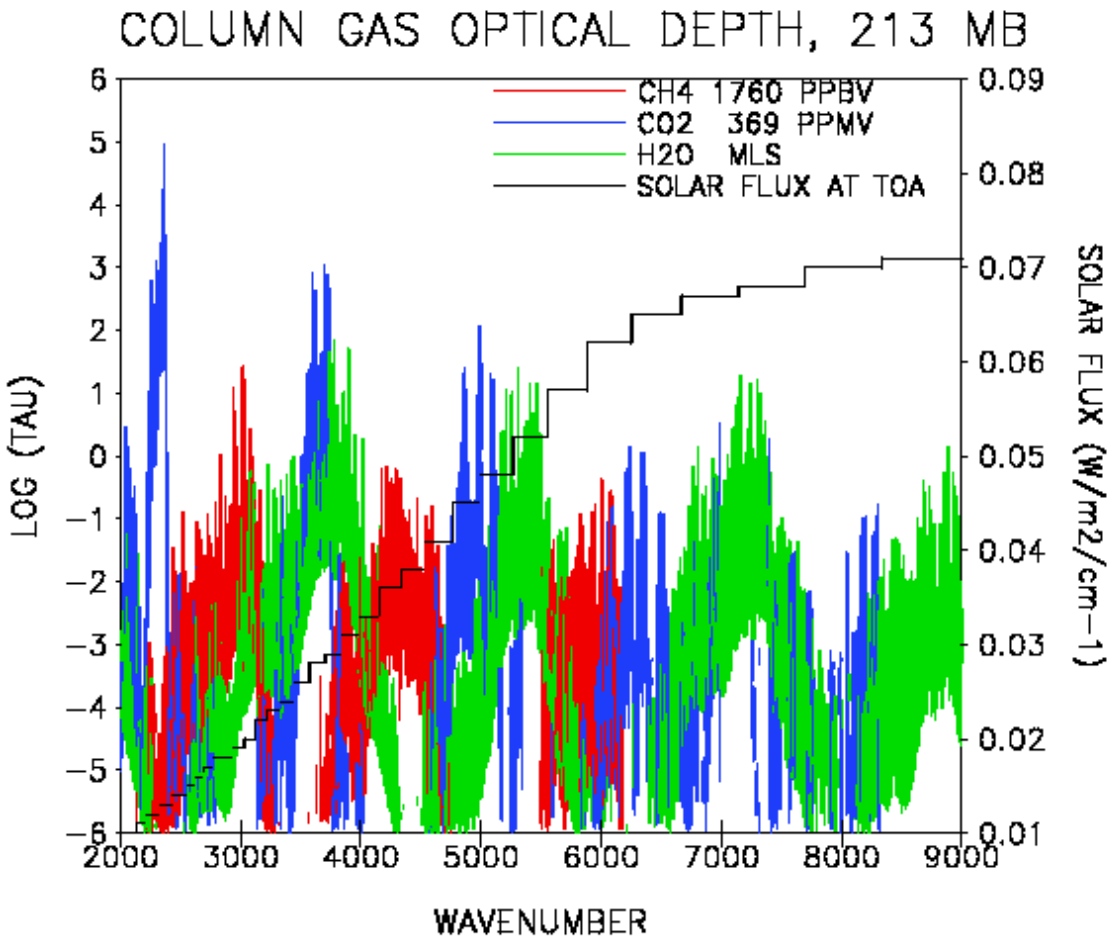
Shortwave



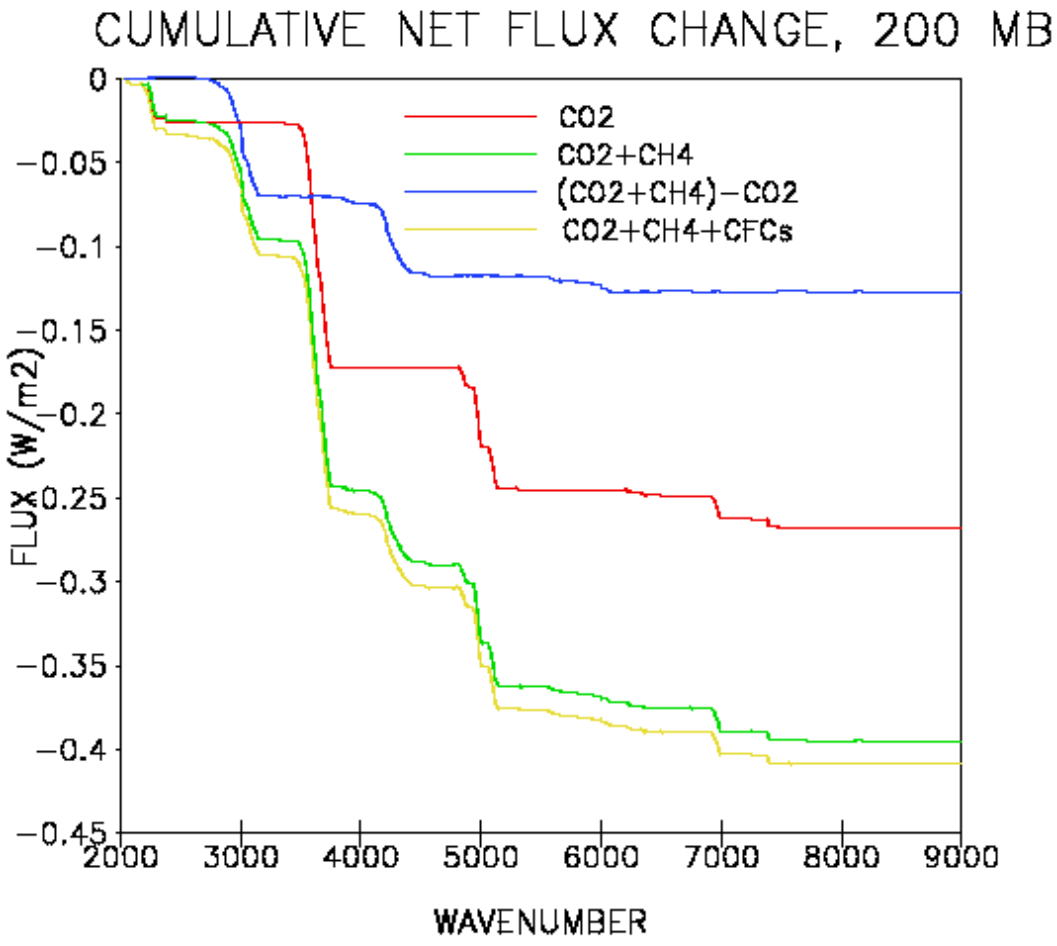
Longwave: Some models have upper tropospheric cooling, an error in sign.
Shortwave: None of the models treat the shortwave heating by CH4 and N2O.

Collins et al, 2006

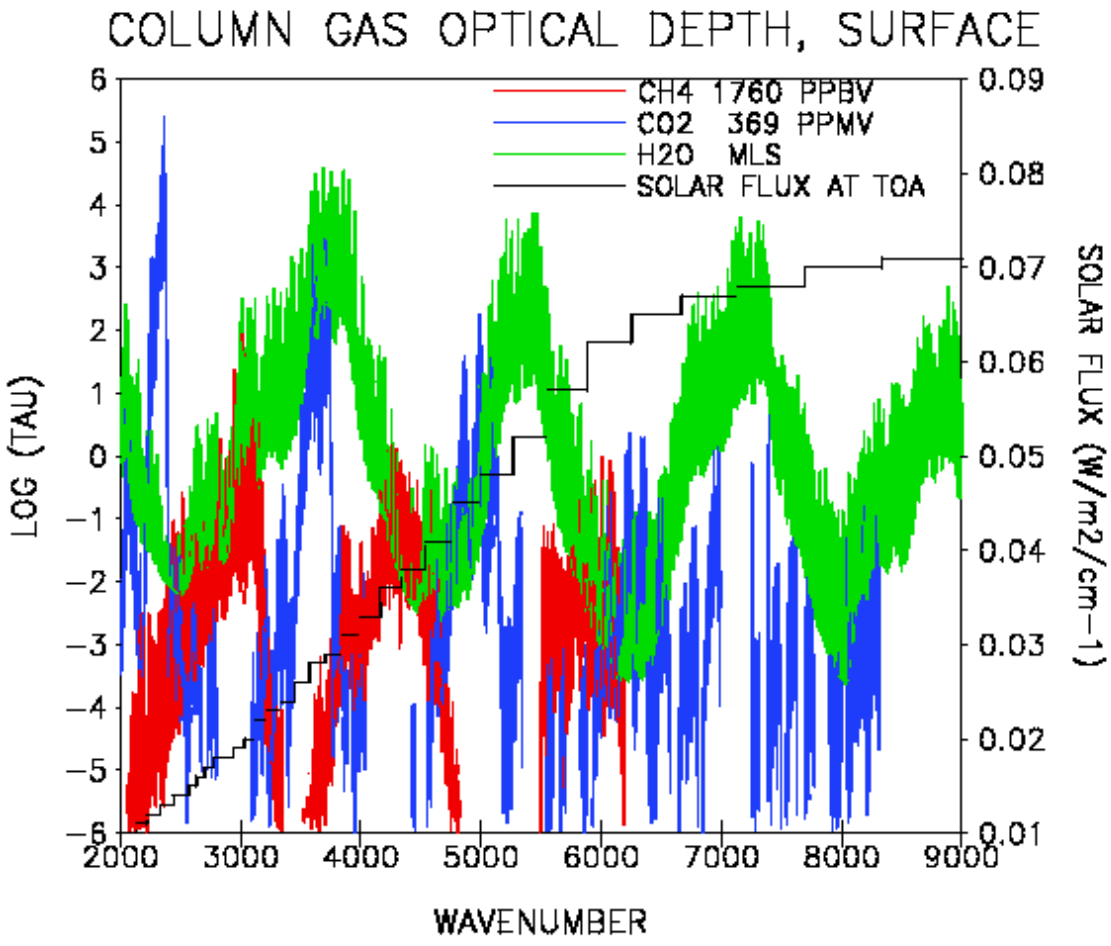
Near-Infrared Optical Depth @ Tropopause



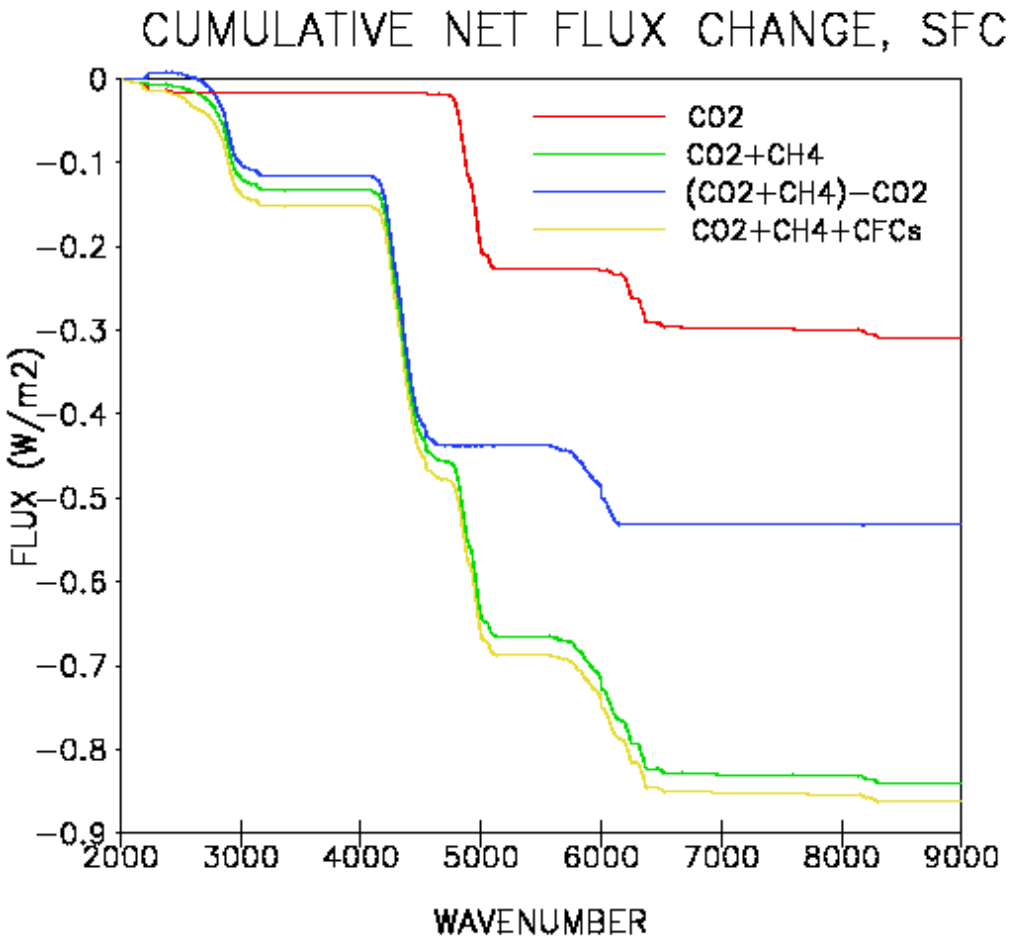
Effects of Methane on Tropopause Fluxes



Near-Infrared Optical Depth @ Surface



Effects of Methane on Surface Fluxes

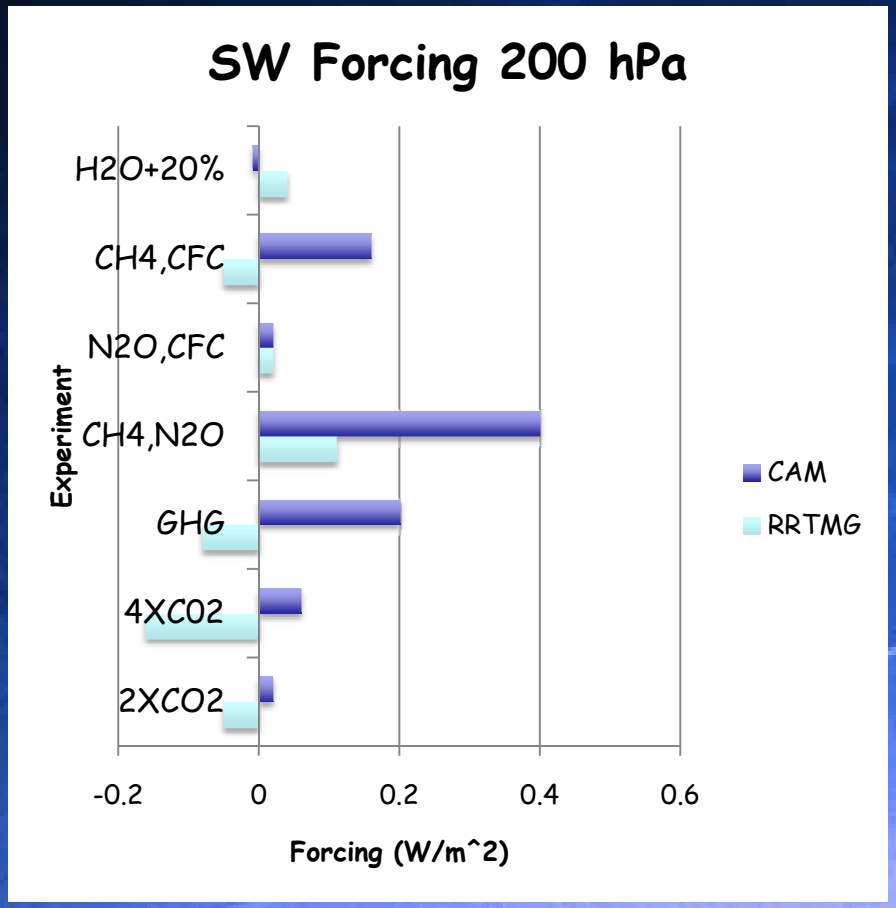


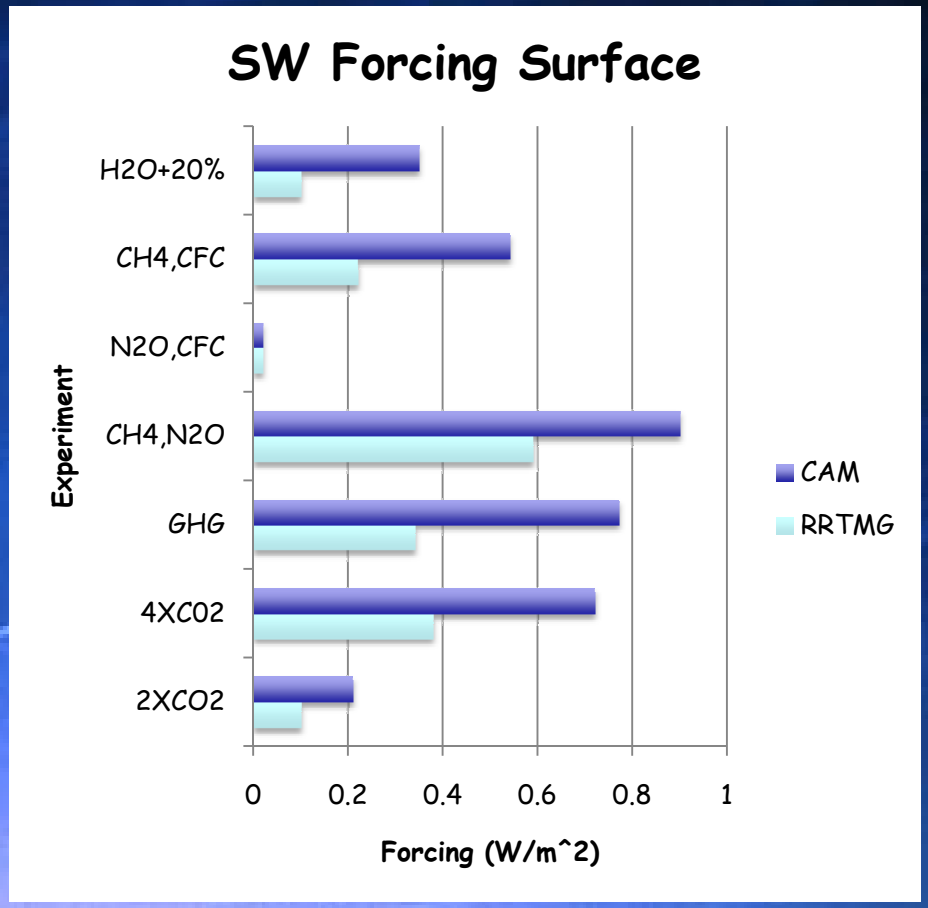
Change in Shortwave Absorption (2000-1860)

Gases	Stratos. Abs.	Tropos. Abs.	Sfc.
All	0.55	0.44	-0.86
CH_4+CO_2	0.53	0.43	-0.84
CO_2	0.31	0.04	-0.31
(CH_4)	0.22	0.40	-0.53

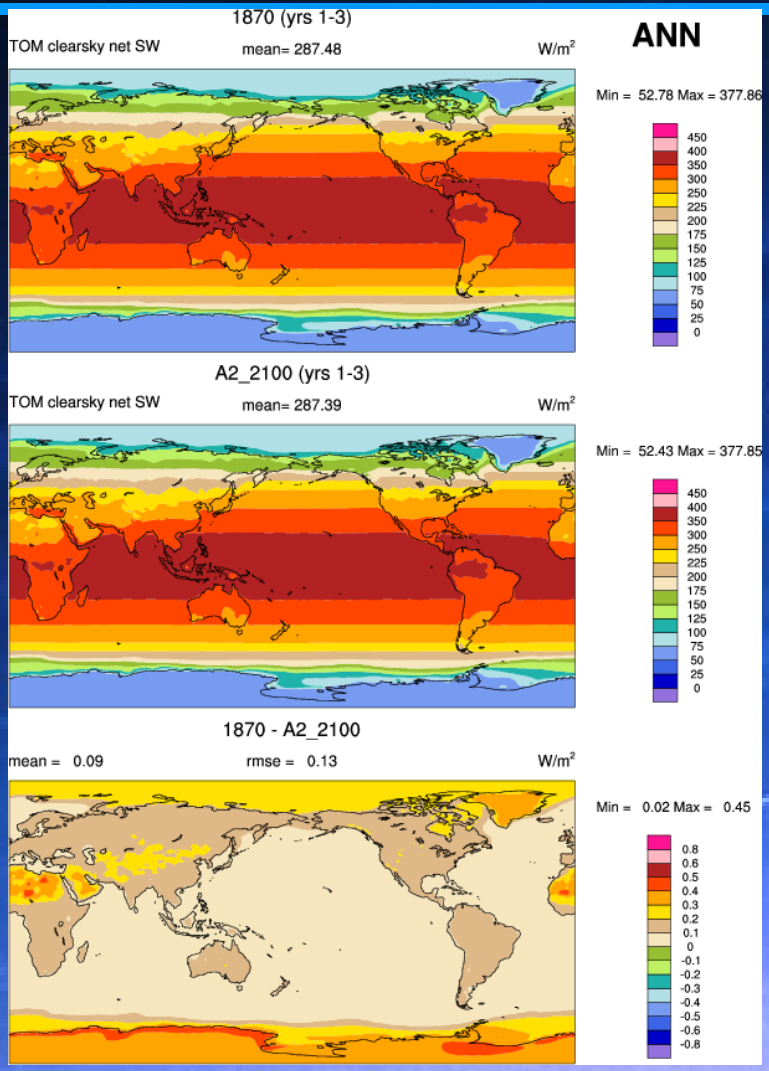
Solar CH_4 comparable to Solar CO_2

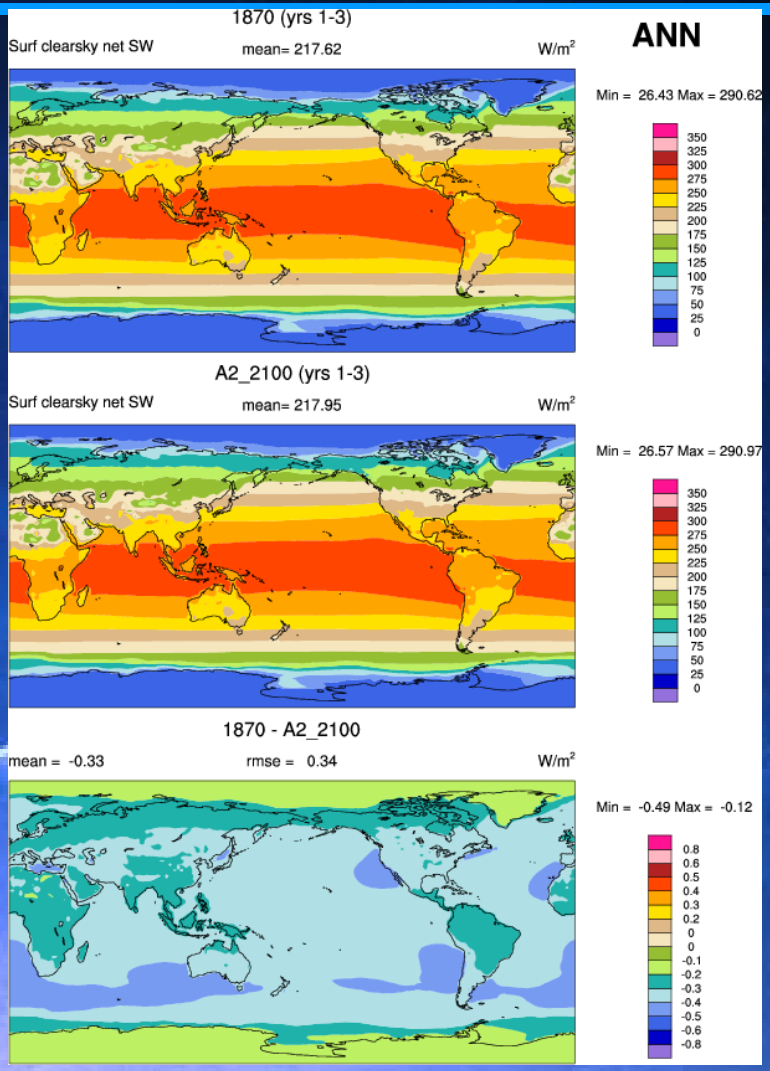
New Radiation Code in CCSM



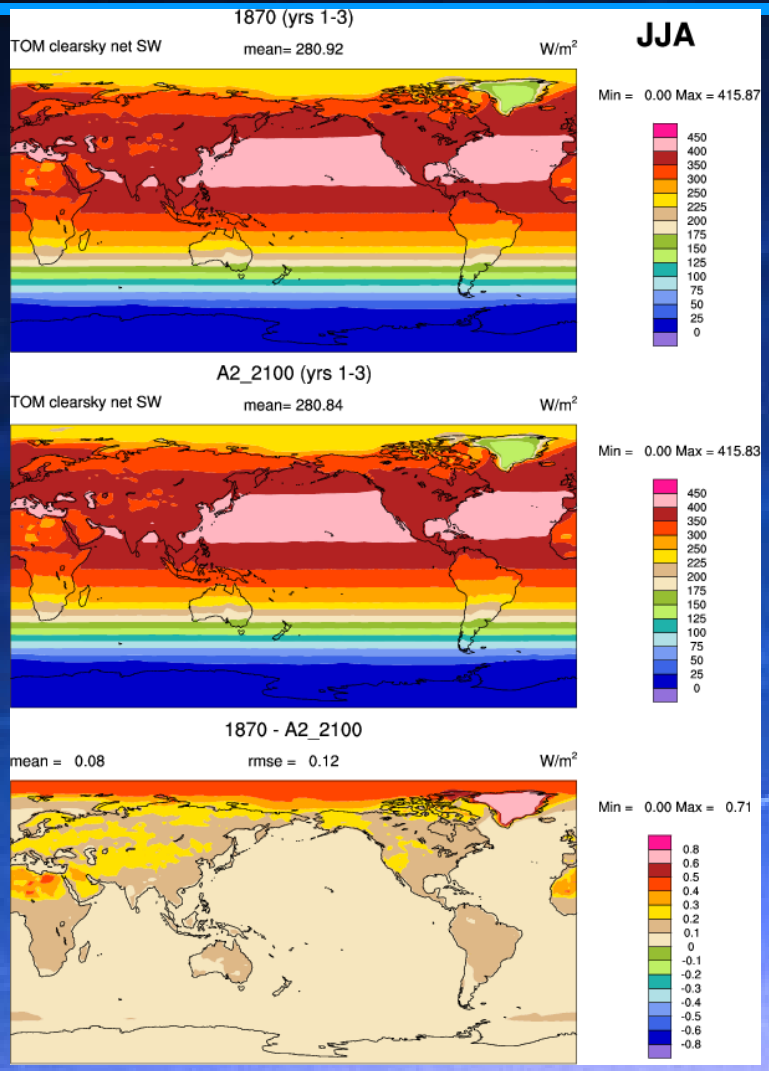


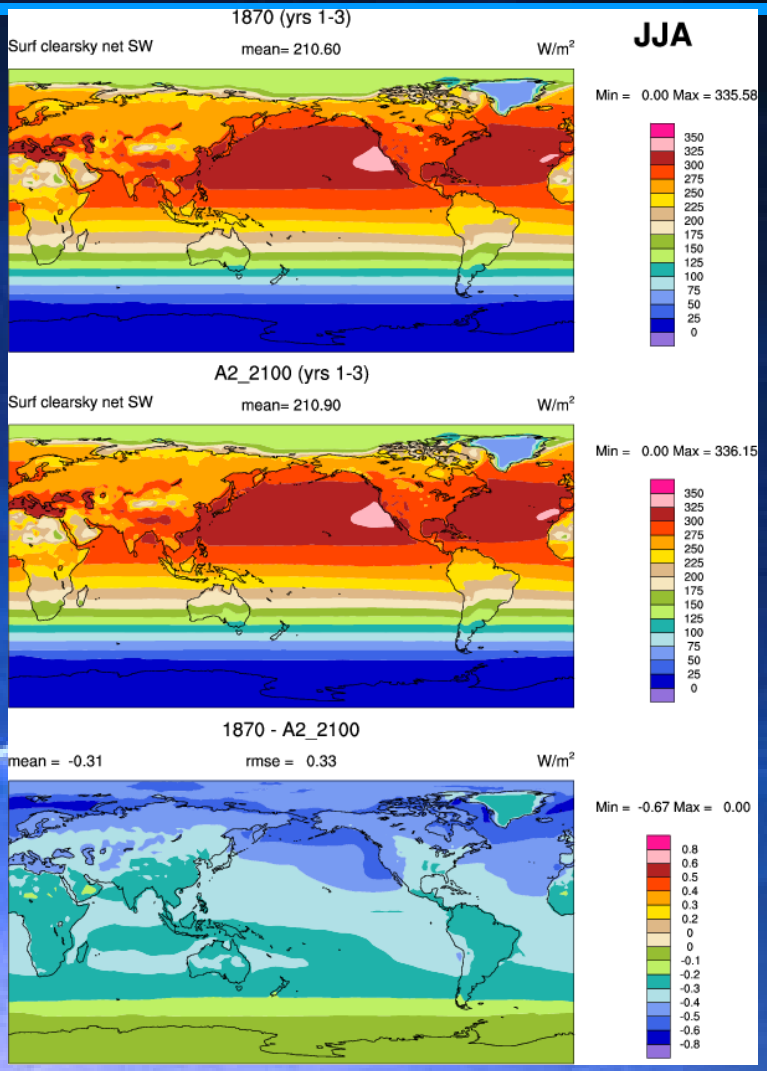
Annual Forcing: 2100 (A2) - 1870





Seasonal Forcing: JJA





Results

- Aerosol reduction in surface insolation is balanced by reduction in surface heat exchange with the atmosphere.
- Absorption generally stabilizes the lower atmosphere.
- Effects of methane on sunlight have been omitted from climate models used for future climate and paleoclimate.
- The solar forcing by methane is comparable to the solar forcing by carbon dioxide.
- The forcing by methane is particularly large in the winter hemisphere and is further enhanced over ice
- The tropical hydrological cycle is generally decelerated by absorption by aerosols, GHGs, and water vapor.

Future research challenges

- What is the actual atmospheric shortwave absorption?
- What is the actual contribution of aerosols to this absorption?
- How are the sources of absorptive aerosols changing in time?
- How are the sources of CH4 and N2O changing in time?
- What are the implications for the global hydrological cycle?