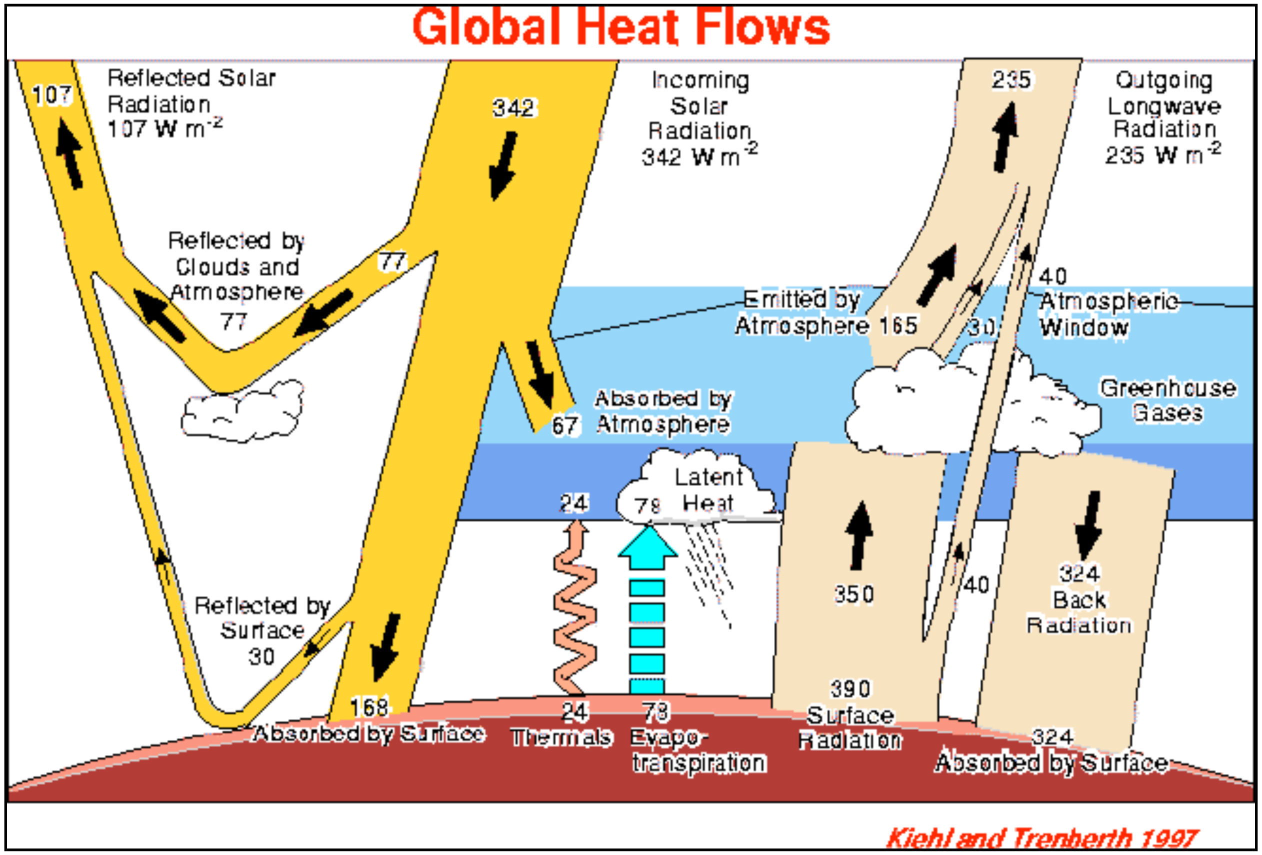
Radiative Processes

Bill Collins

UC Berkeley and Lawrence Berkeley Lab

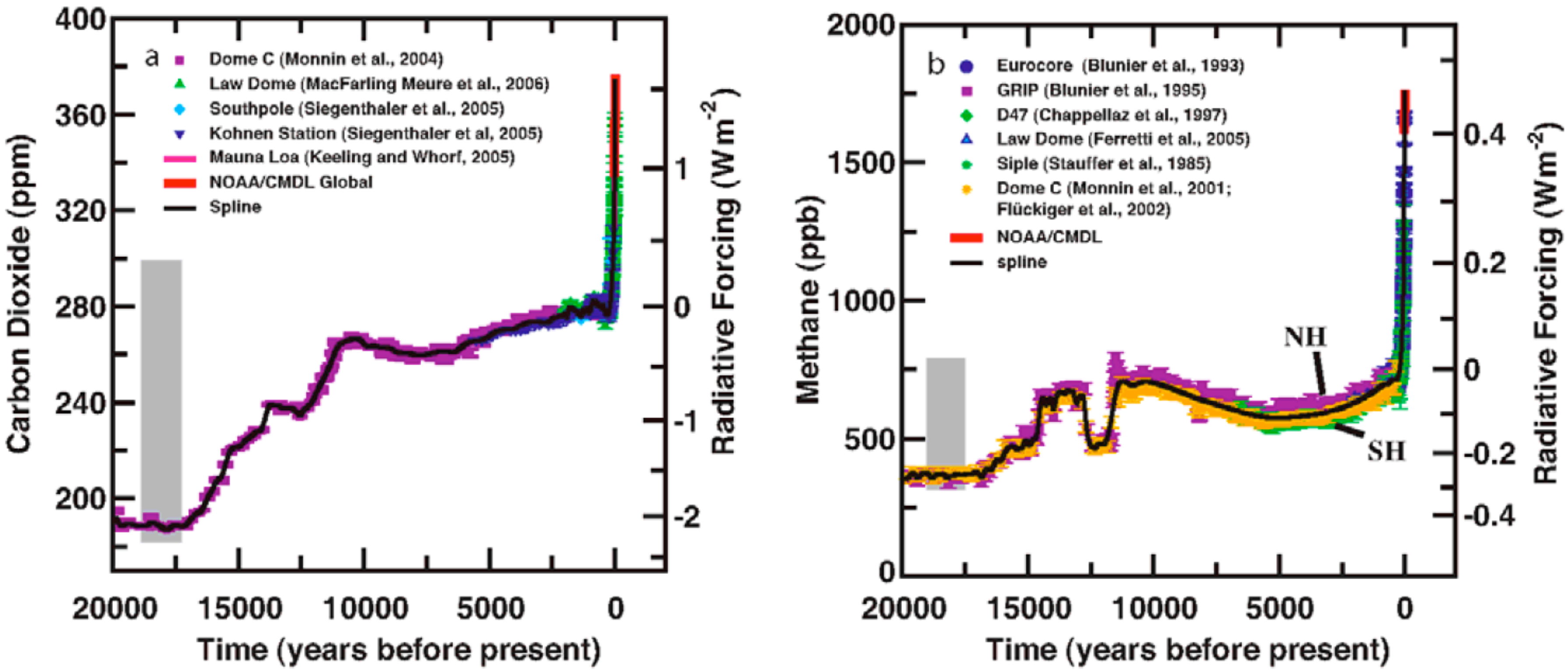
wdcollins@berkeley.edu

The energy budget of the Earth's climate



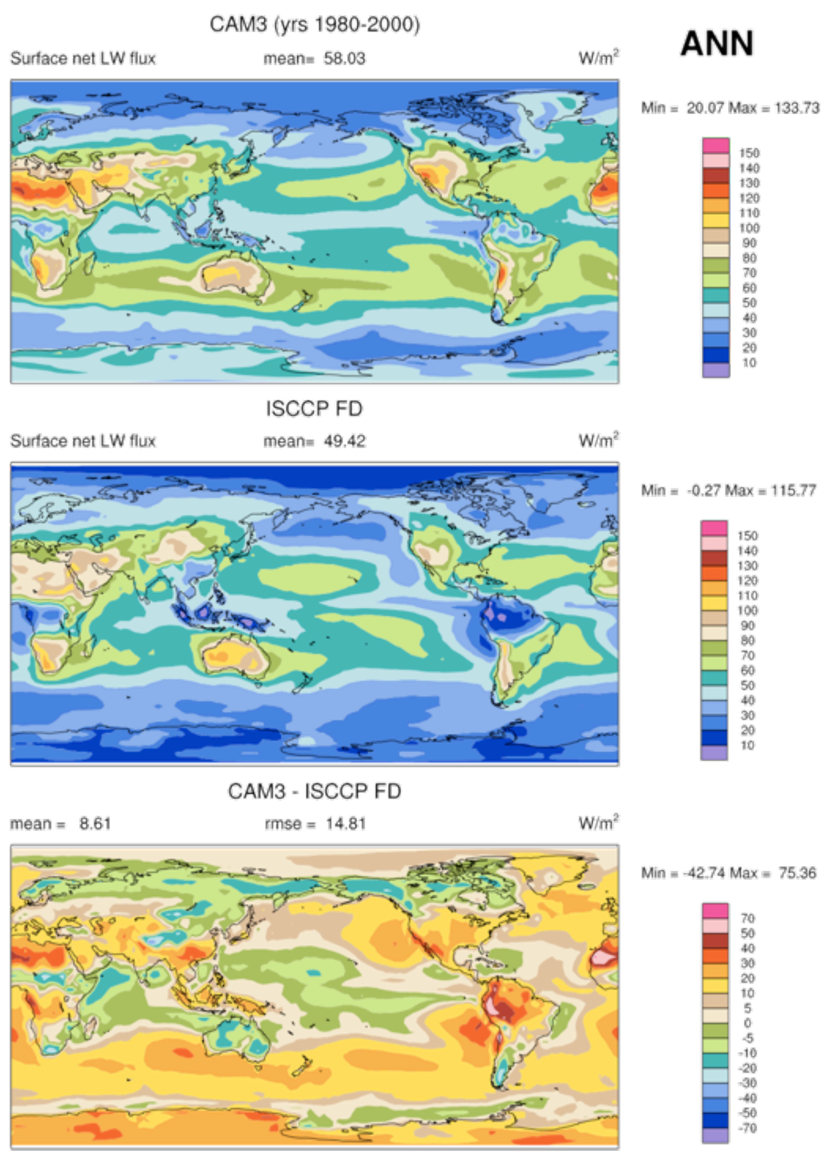
Gas	Absorption
CO_2	1
O_2	2
O_3	14
H_2O	43

Changes in atmospheric composition

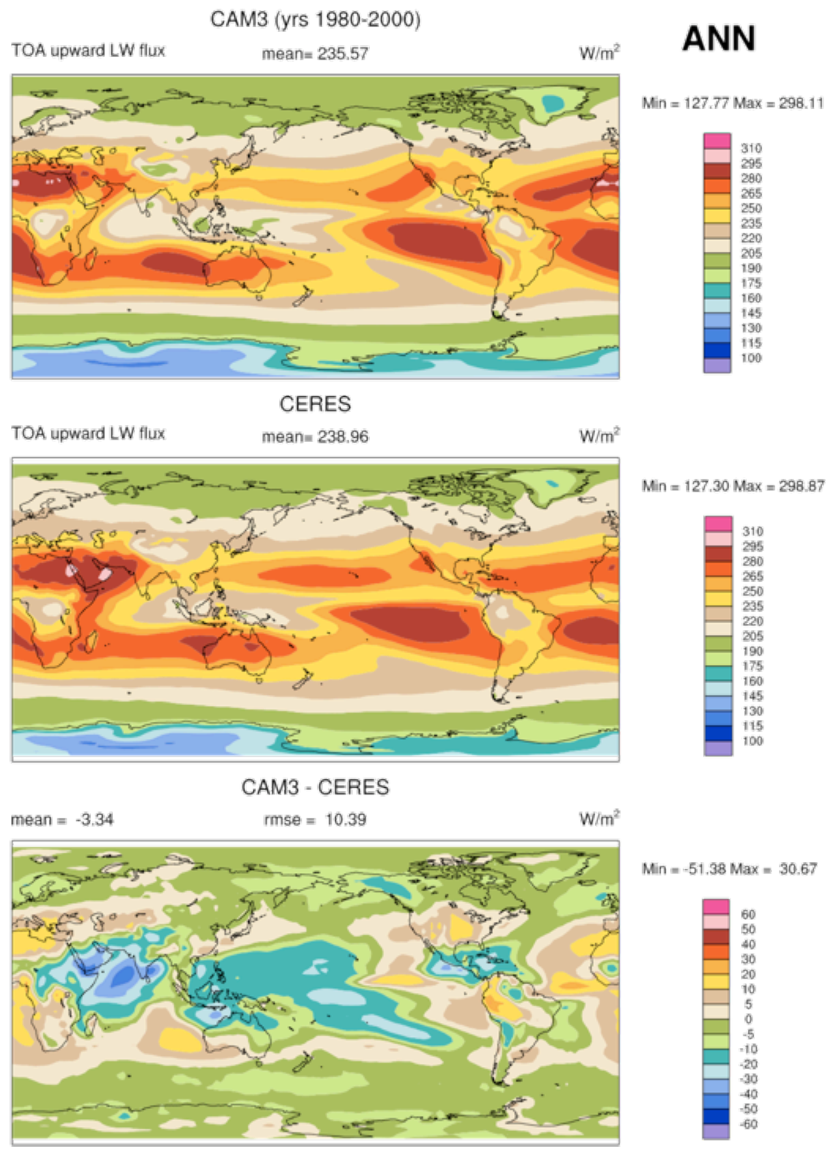


- Concentrations of greenhouse gases are highest in 650K years.

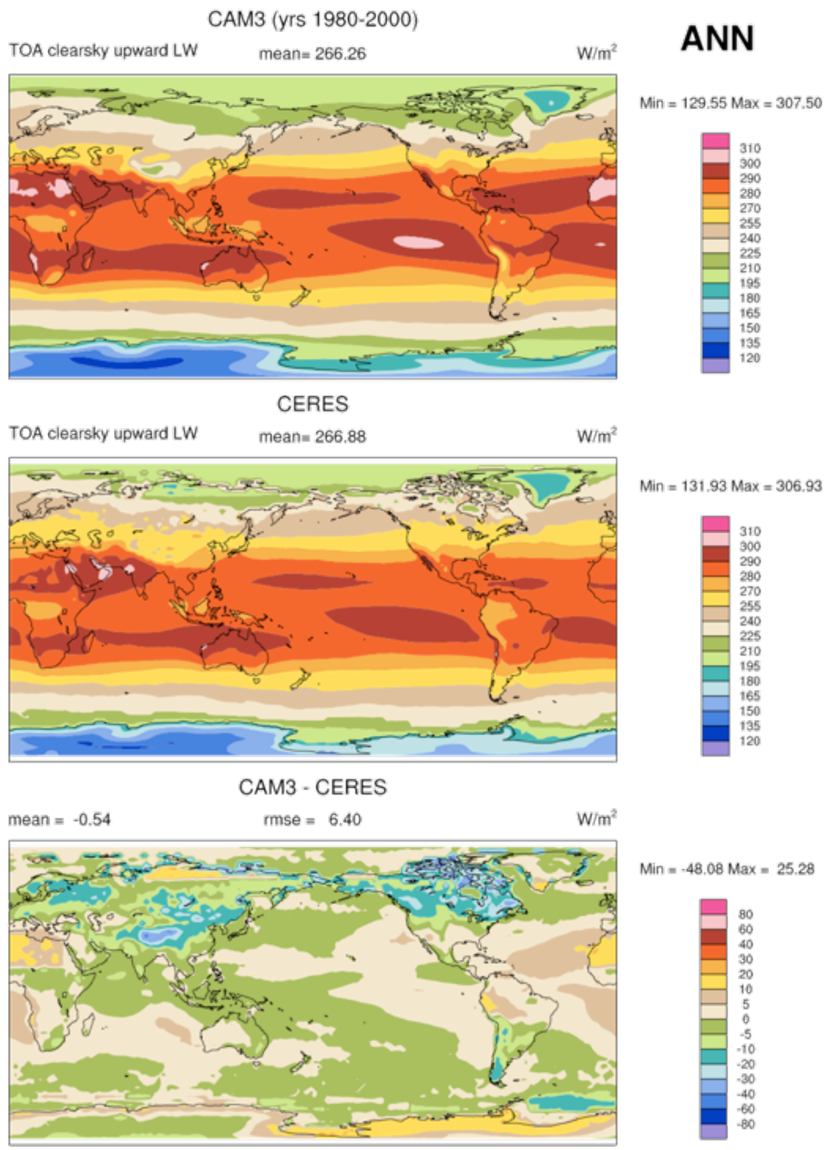
Net surface longwave (IR) flux



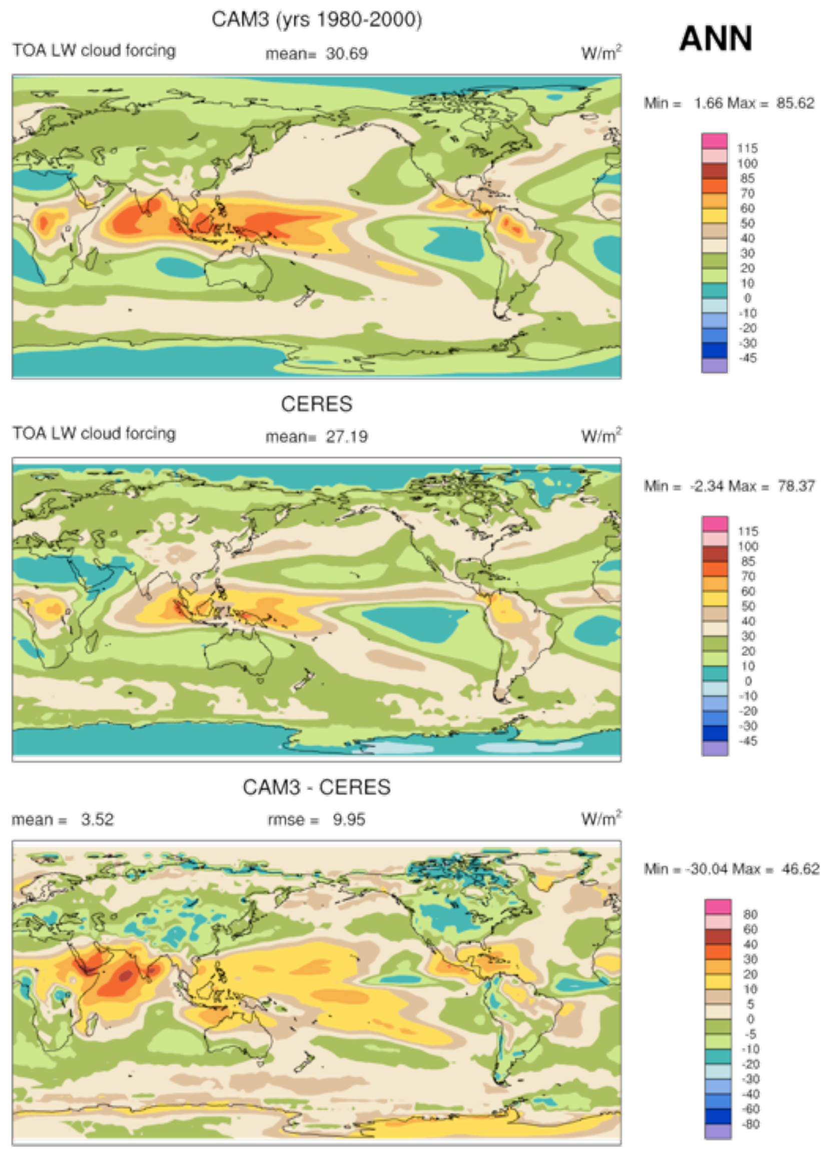
Longwave emission to space



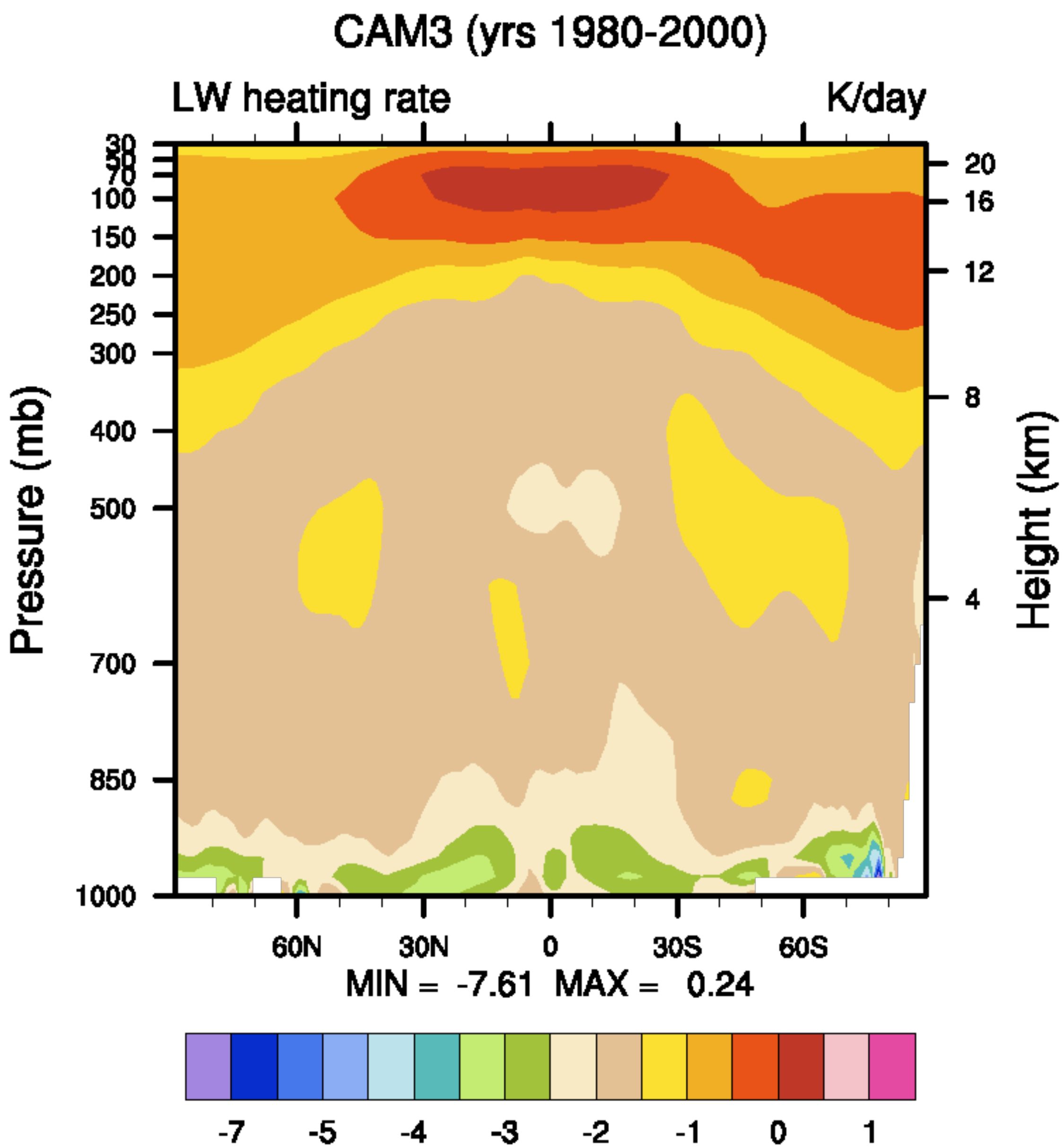
Longwave emission, Cloud-free



Longwave cloud radiative effects



Longwave heating (cooling) rate



The equations of radiative transfer

The basic equation of radiative transfer is

$$dI_\lambda = -I_\lambda d\tau_\lambda + S_\lambda$$

where

$$\begin{aligned} I_\lambda &= \text{radiance} \\ \lambda &= \text{wavelength} \\ \tau_\lambda &= \text{optical depth} \\ S_\lambda &= \text{source function} \end{aligned}$$

The optical depth measures the number of interactions with the atmospheric constituents.

For incoming sunlight (direct beam), the solution is

$$I_\lambda(\tau_\lambda) = I_\lambda(0)\exp(-\tau_\lambda)$$

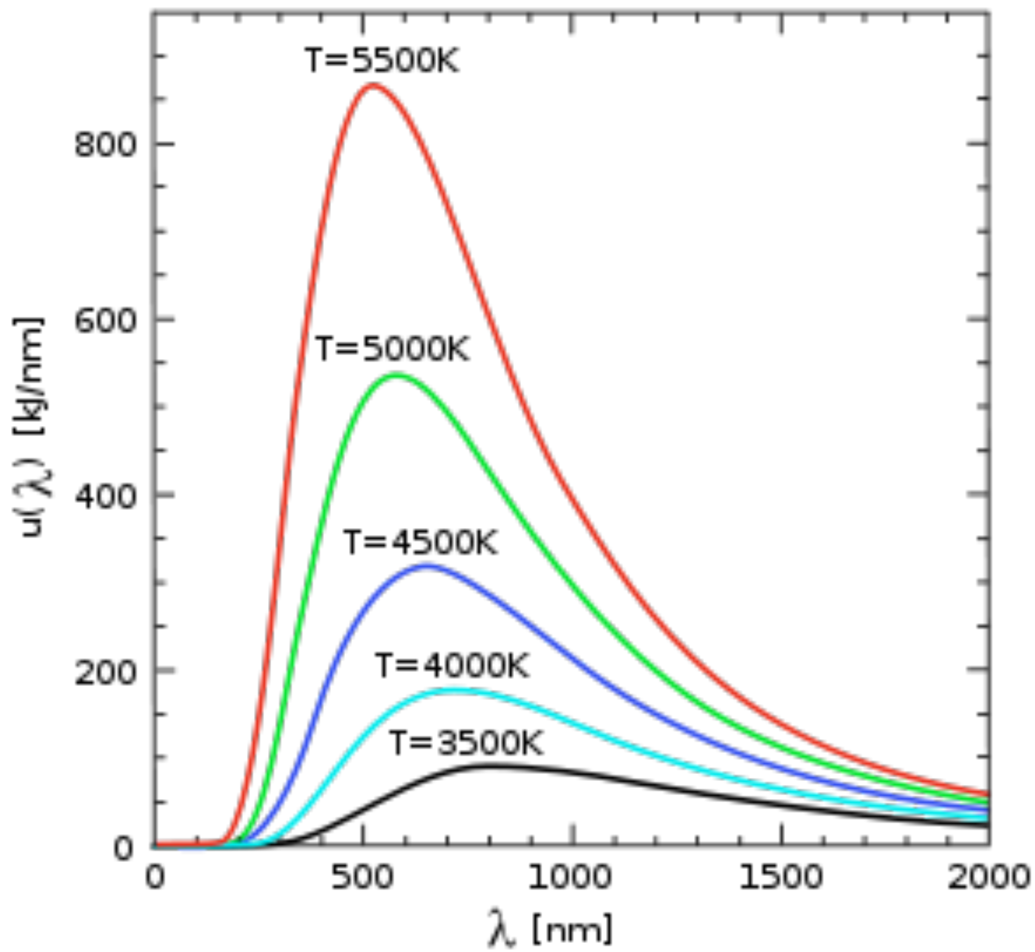
In the infrared, the solution is approximately

$$I_\lambda(\tau_\lambda) = I_\lambda(0)\exp(-\tau_\lambda) + \int S_\lambda(\tau')\exp(\tau' - \tau_\lambda)\,d\tau'$$

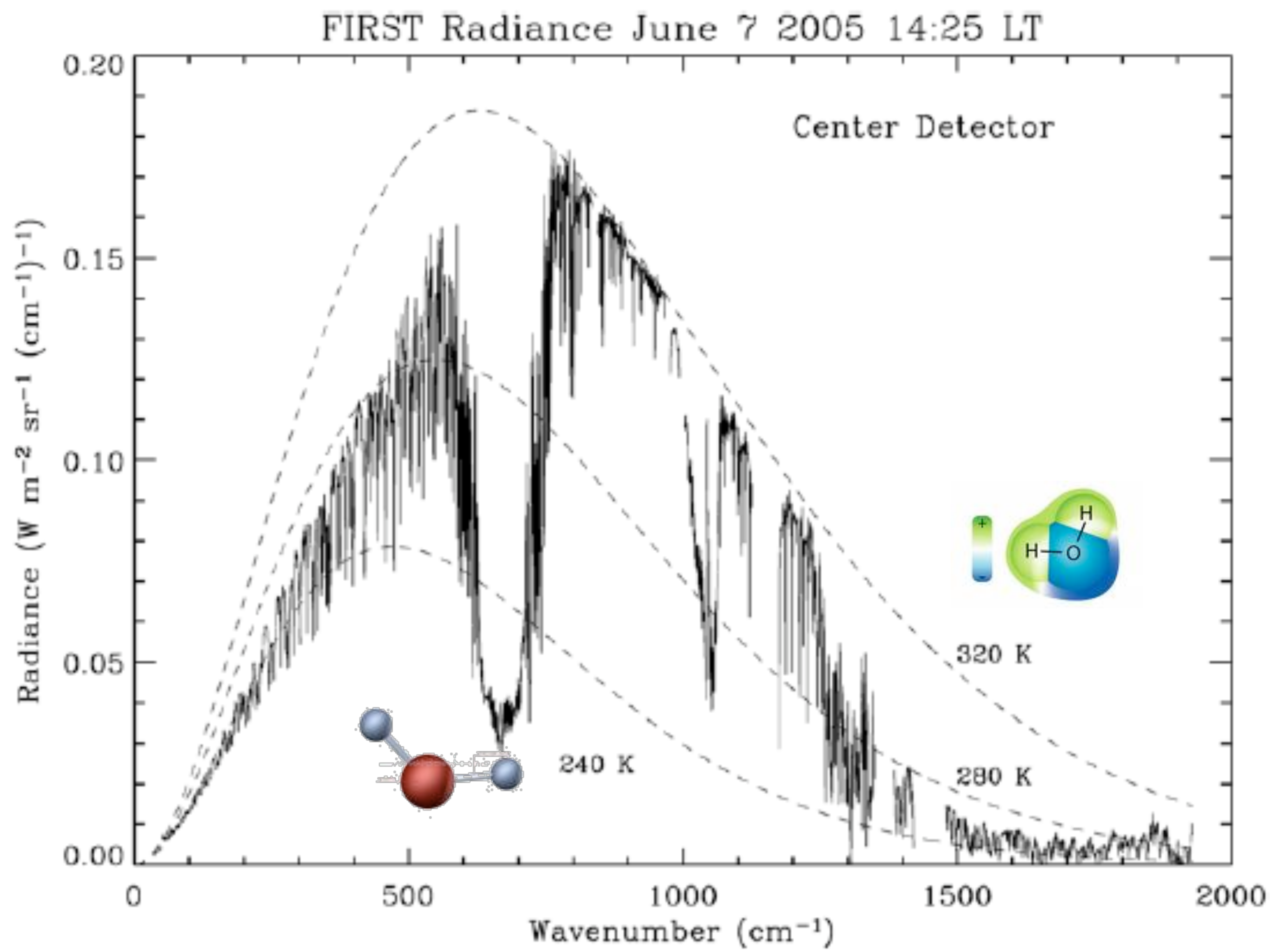
where

$$\begin{aligned} S_\lambda(\tau') &= B_\lambda \\ B_\lambda &= \text{Planck function} \end{aligned}$$

The Planck Function

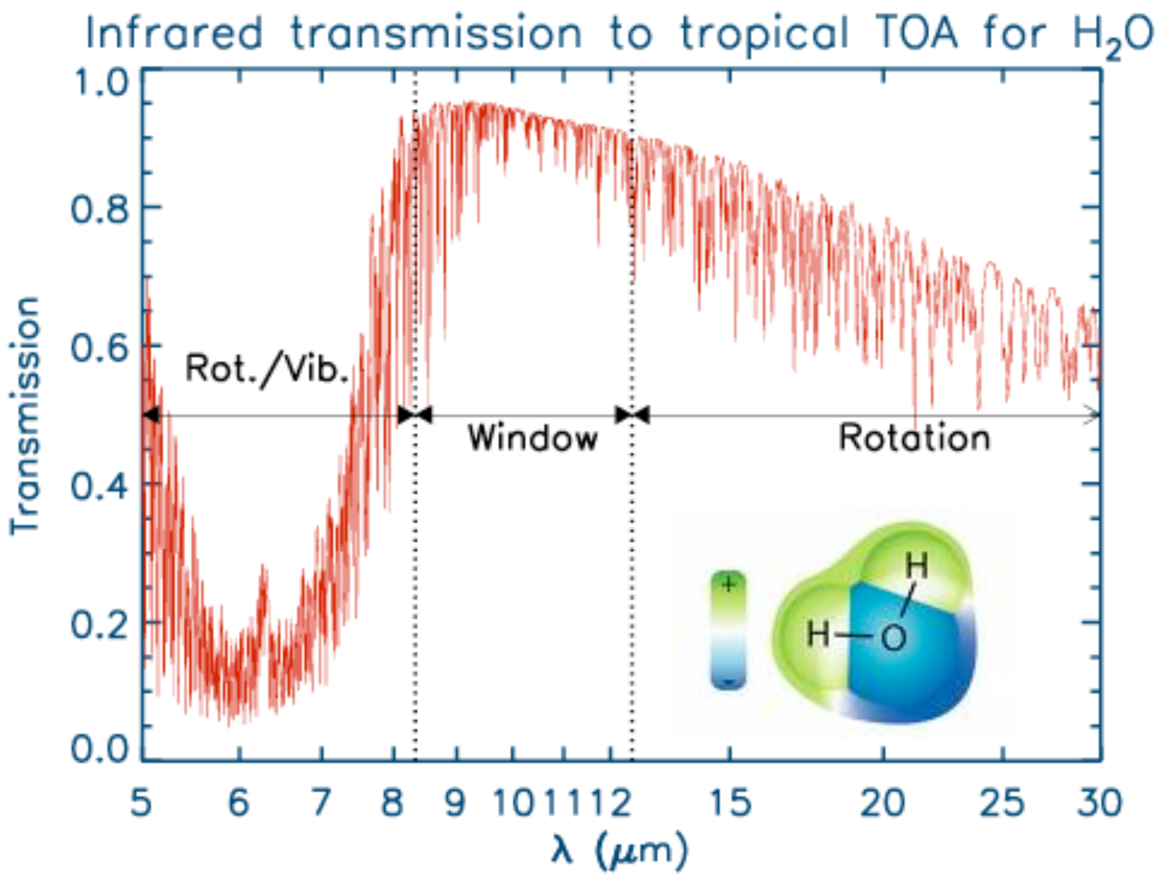


Infrared spectrum of emission

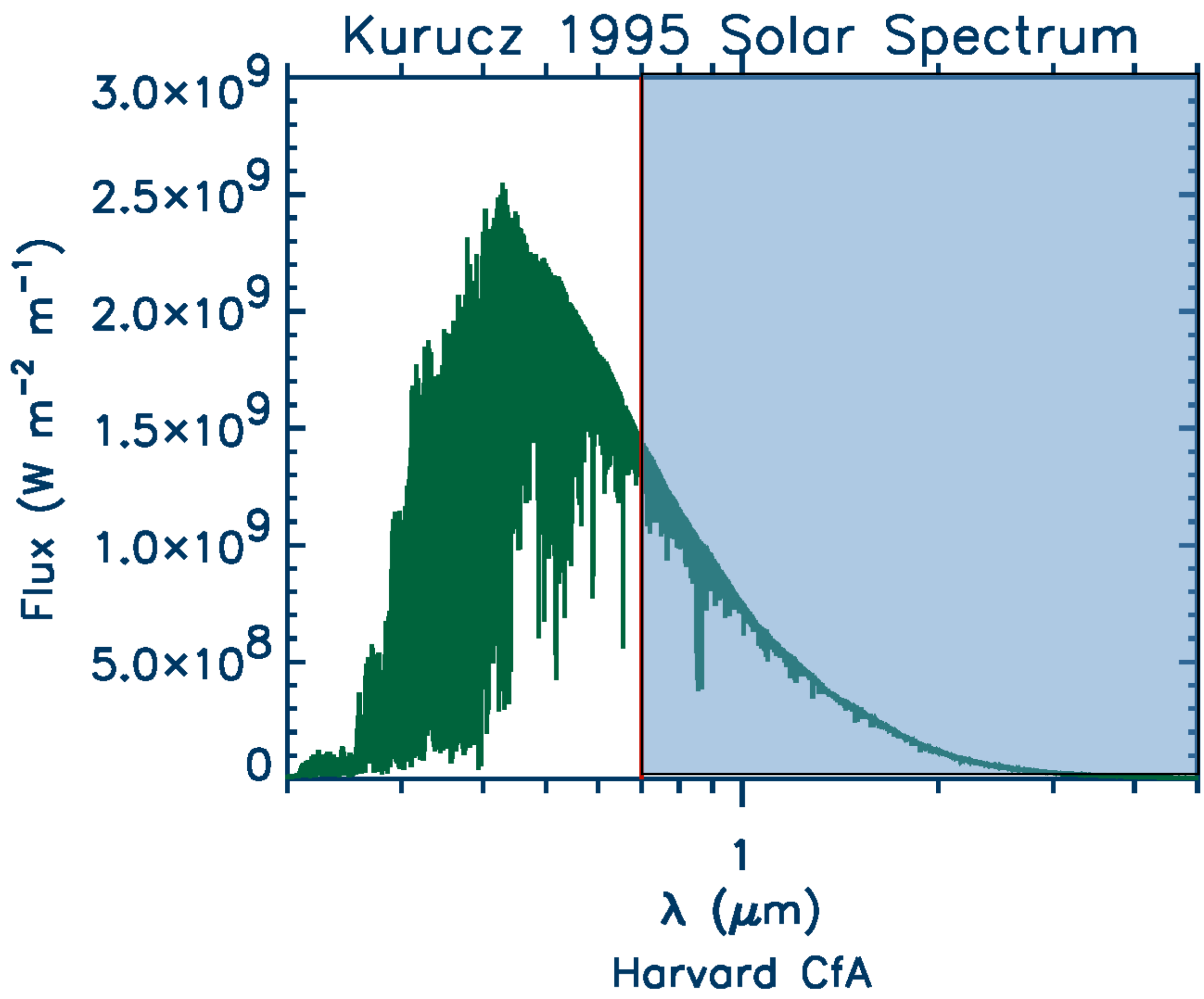


Mlynczak et al, 2006

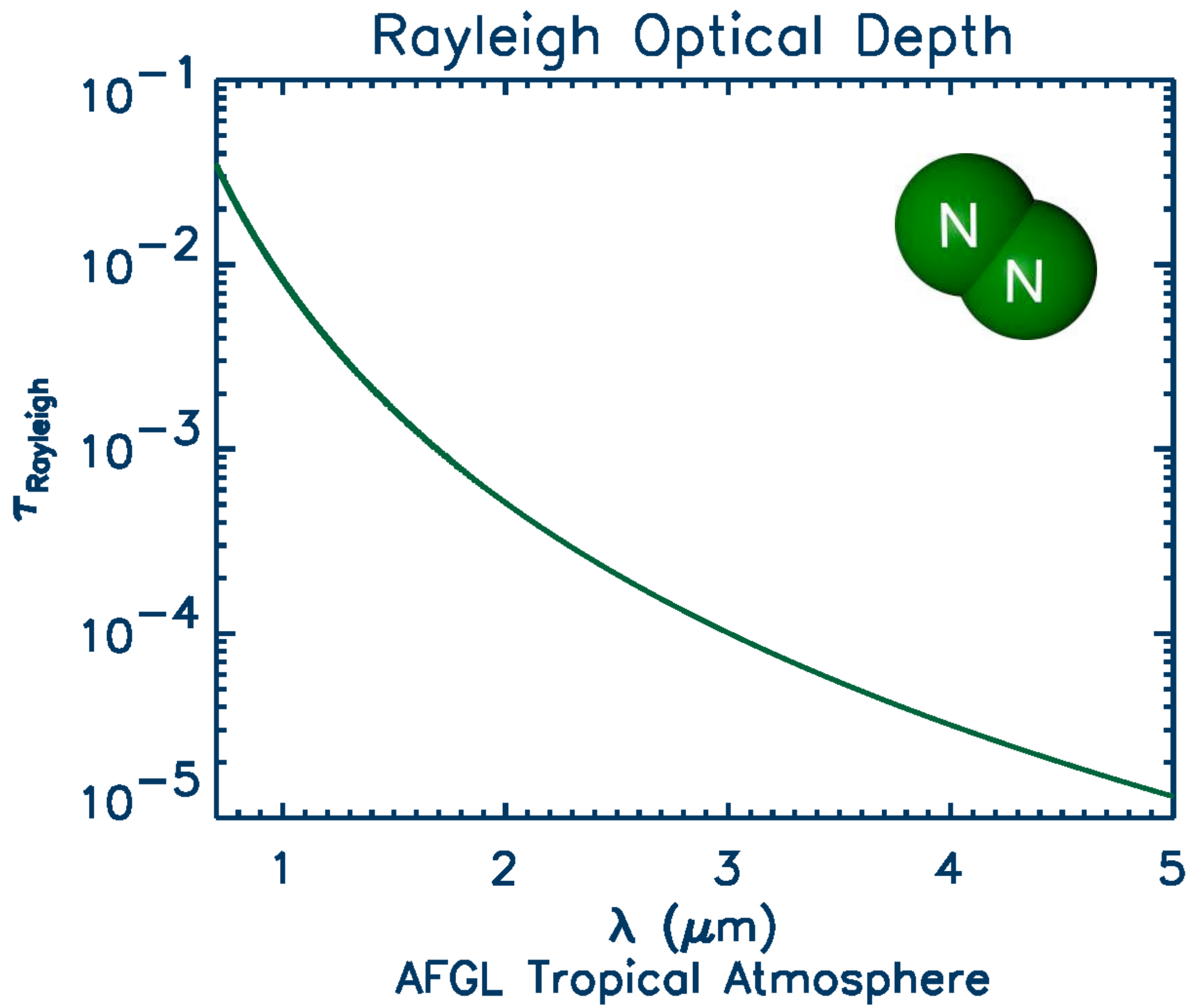
Effects of H_2O on IR emission



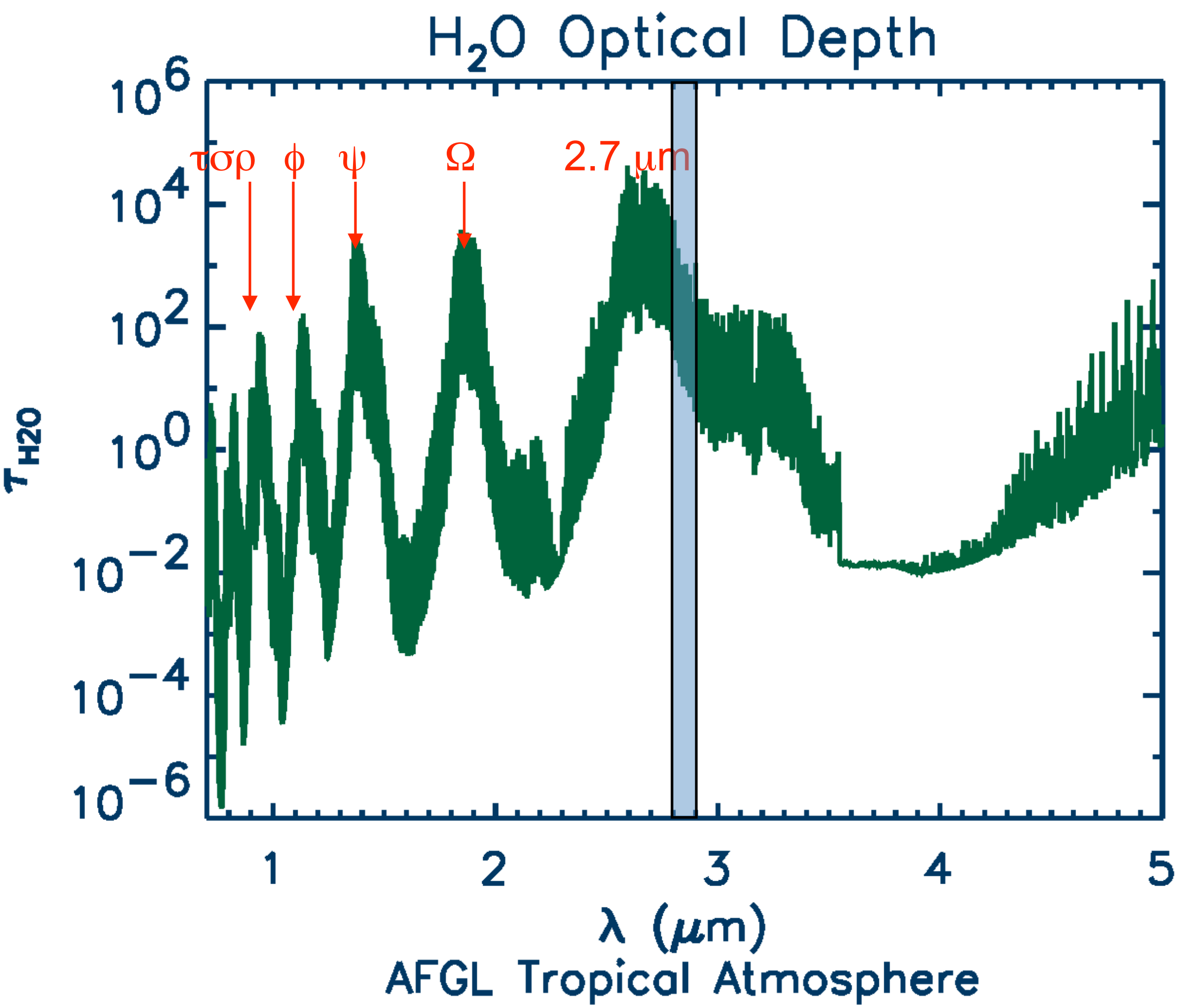
Solar insolation at top of atmosphere



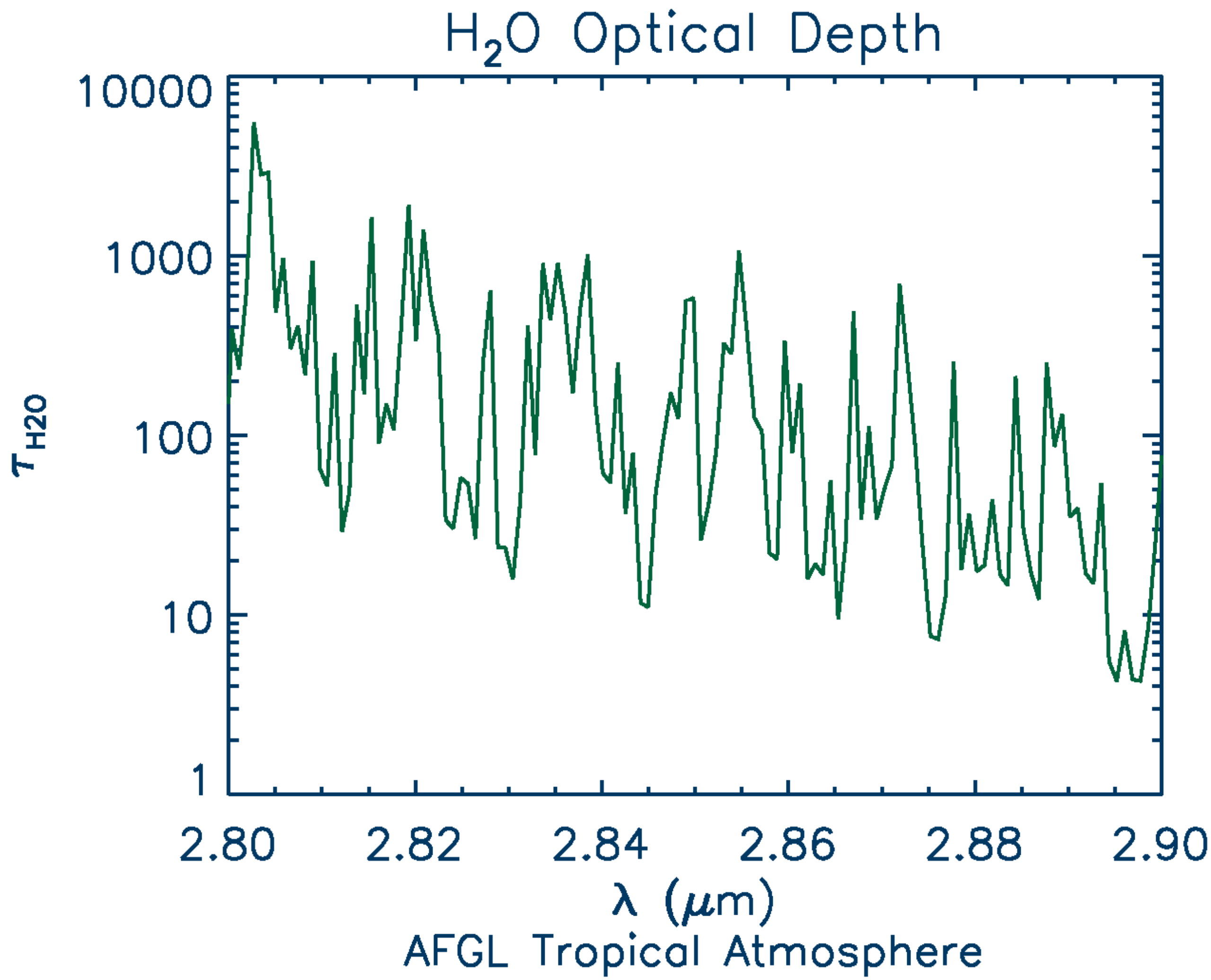
Rayleigh scattering



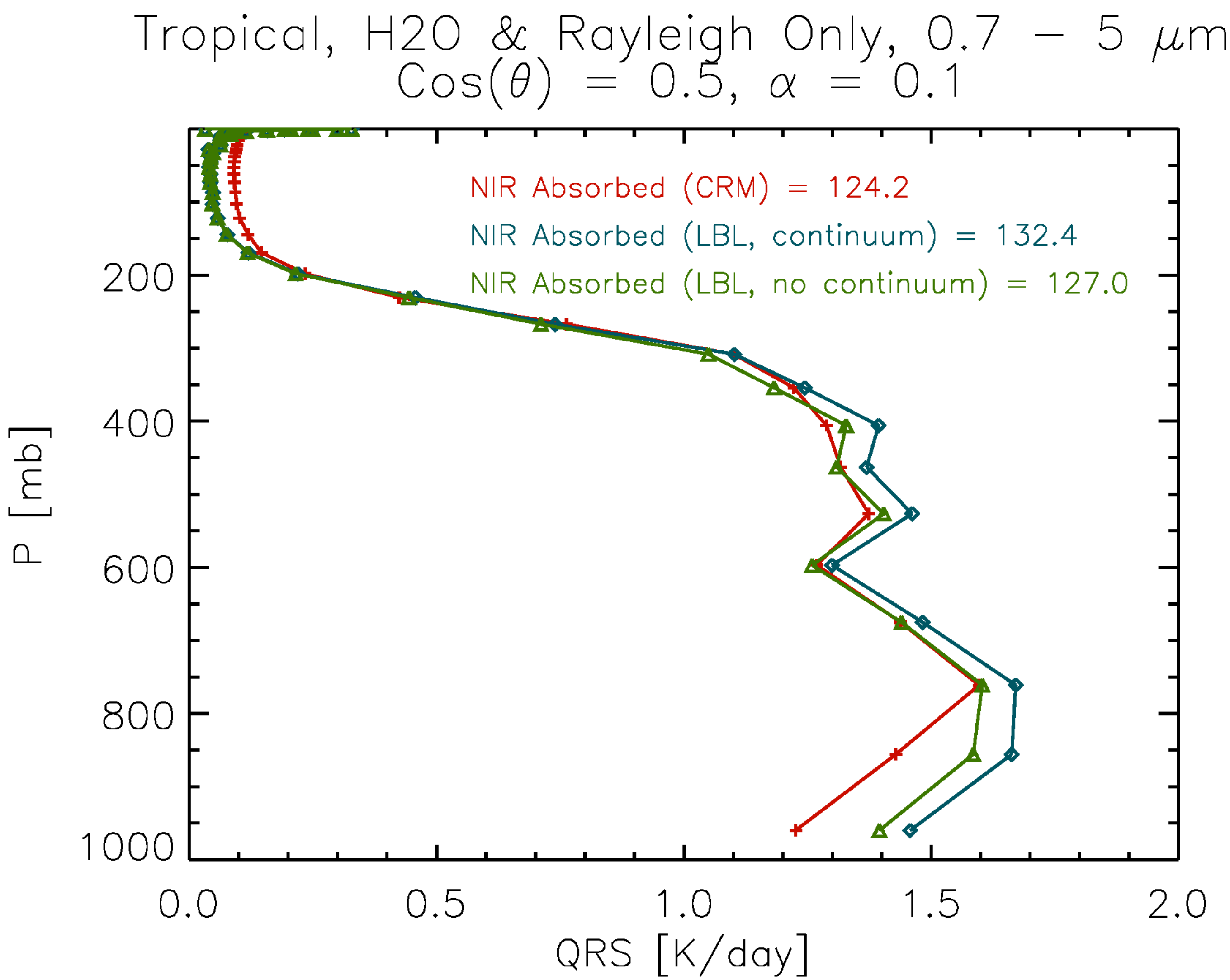
Effects of H_2O on solar spectrum



Effects of H_2O: vibration-rotation lines

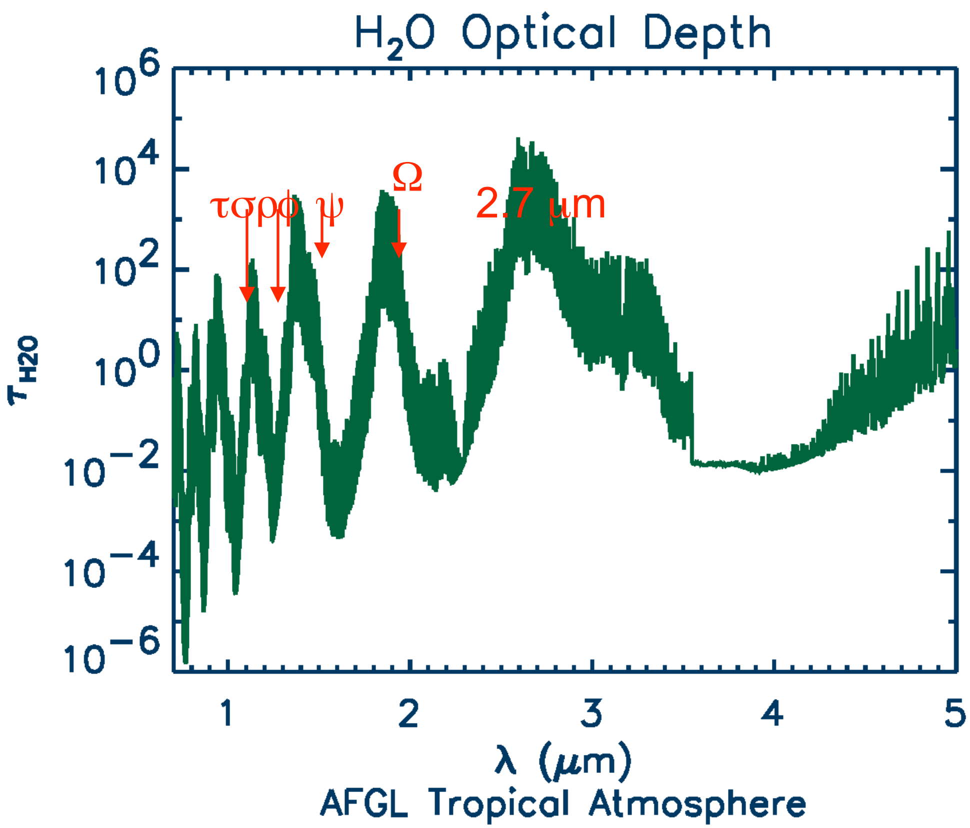


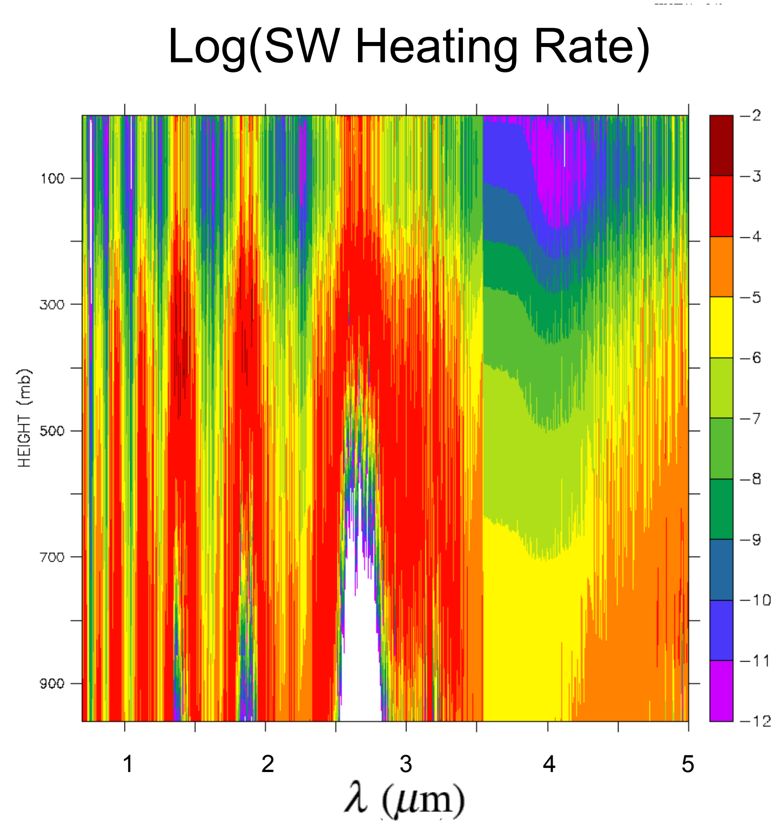
Effects of H_2O on solar heating rates



Challenge of radiative parameterization

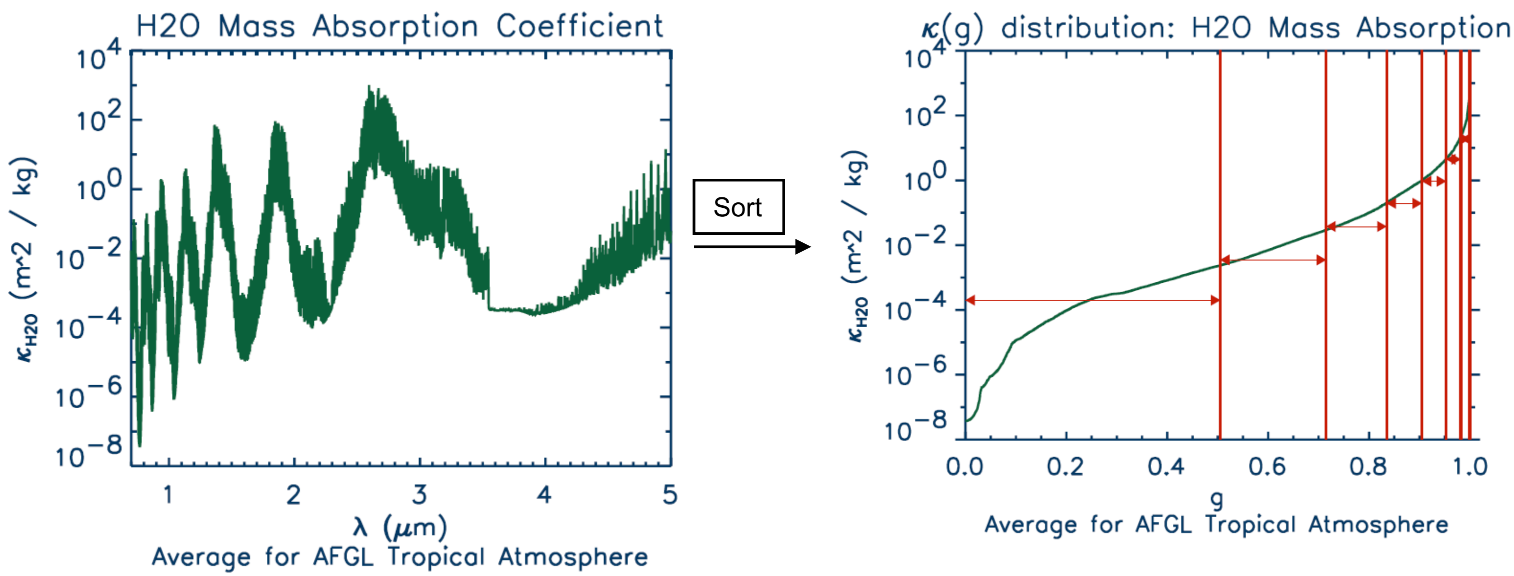
The solar and infrared spectra exhibit variations in extinction, optical depth, and heating rates of ≥12 orders of magnitude.





Collins et al, 2006

k-distribution Band Models

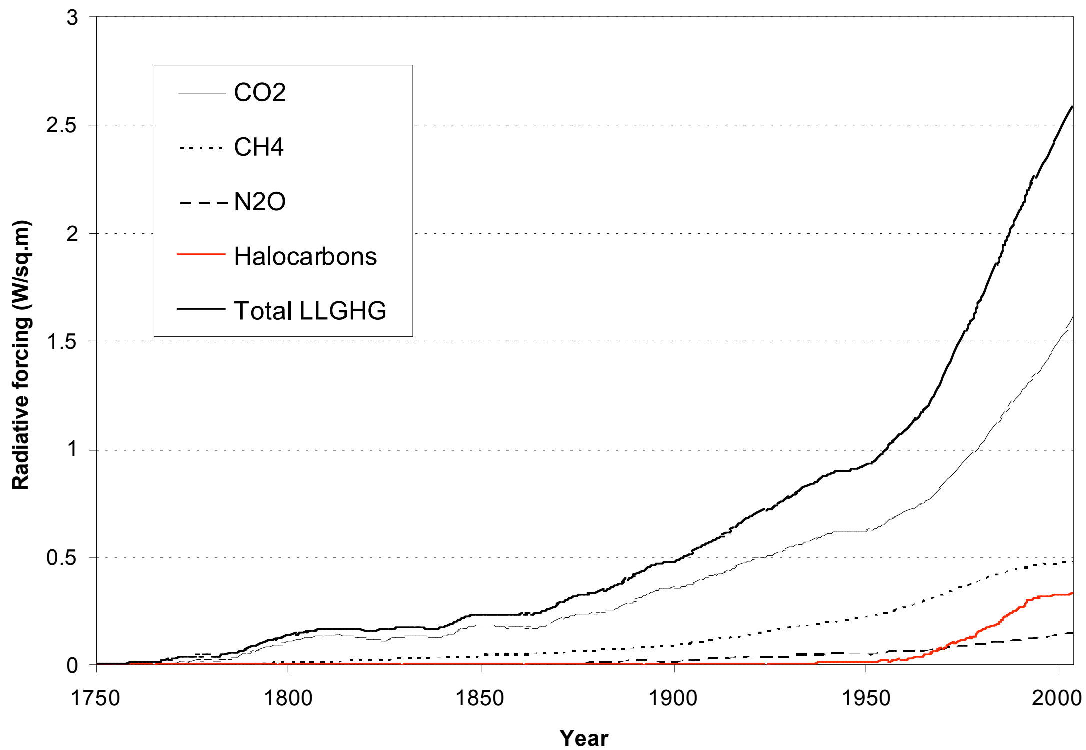


$$T(u) = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} \exp[-\kappa(\lambda)u]\, d\lambda$$

$$T(u \quad \hat{T}(u) \simeq \sum_{i=1}^{N} \exp[-\hat{\kappa}_i u]\; \delta g_i \quad dg$$

- In the k-distribution band model, the absorption coefficients are sorted by magnitude.
- The transmission integral should be much easier to approximate in this sorted form.
- Yet classical approximation methods may not be suitable.
- Are there physically and mathematically optimal methods for approximation?

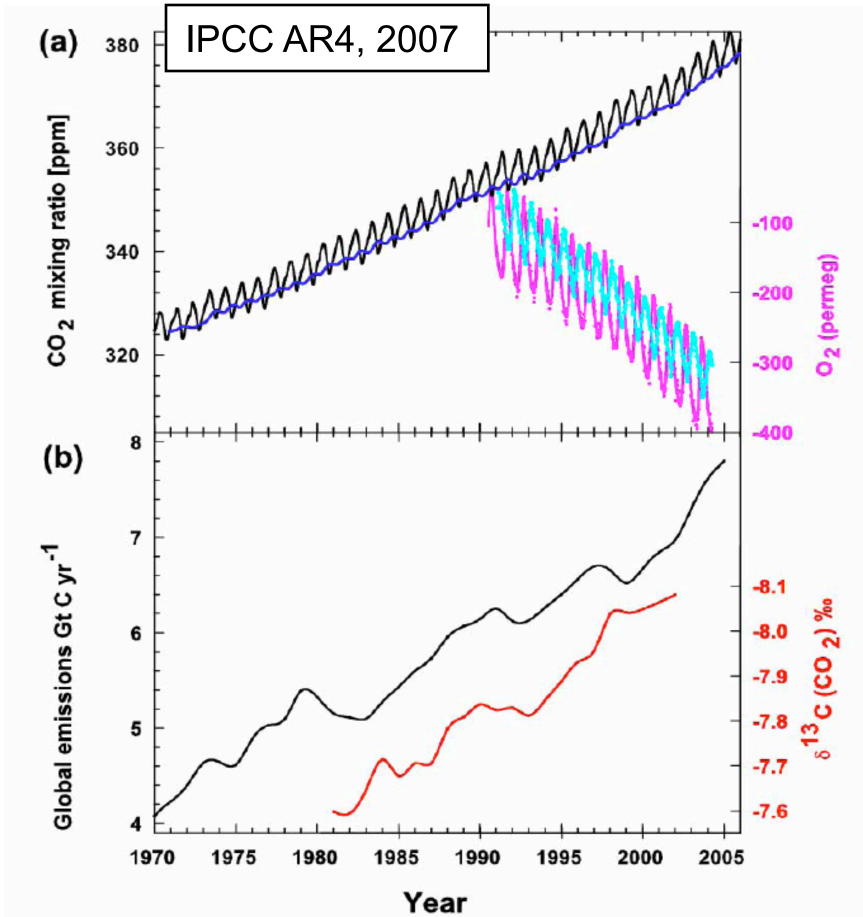
Concept of Radiative Forcing



IPCC AR4, 2007

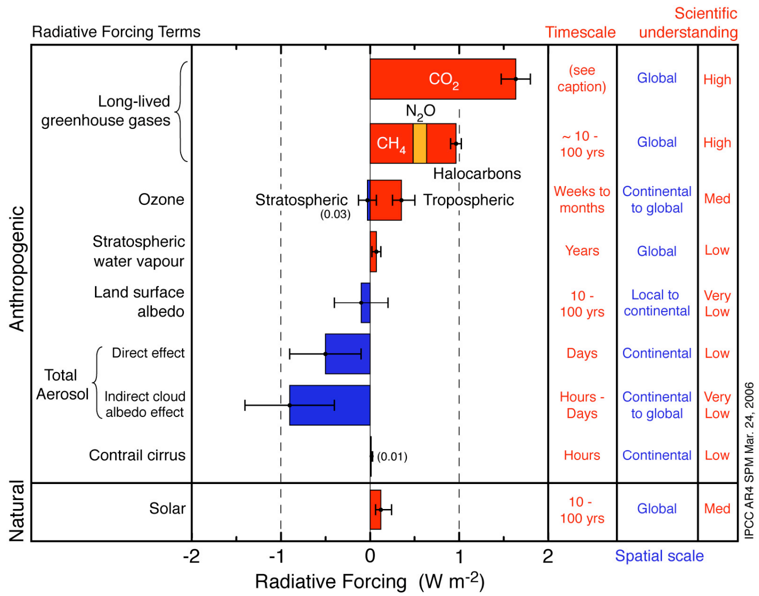
Radiative forcing is an "externally imposed perturbation in the radiative energy budget of the Earth's climate system." (IPCC TAR)

Human-induced greenhouse forcing

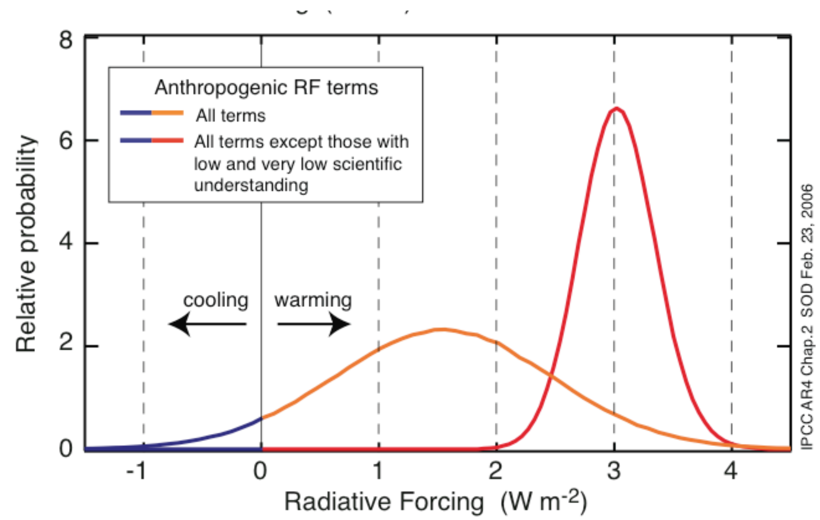


- Concentrations of O_2 and fractions of ^{13}C are decreasing.
- These decreases are most consistent with fossil fuel origin.

Historical Radiative Forcing



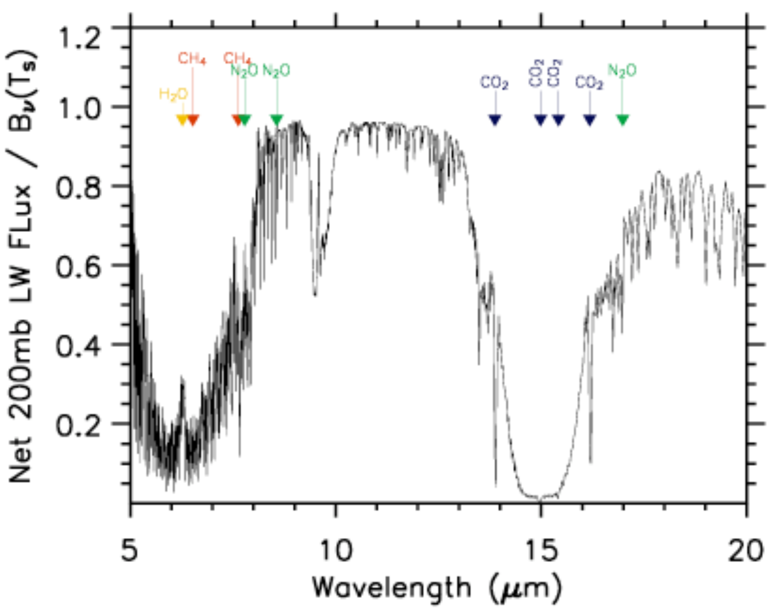
IPCC AR4, 2007



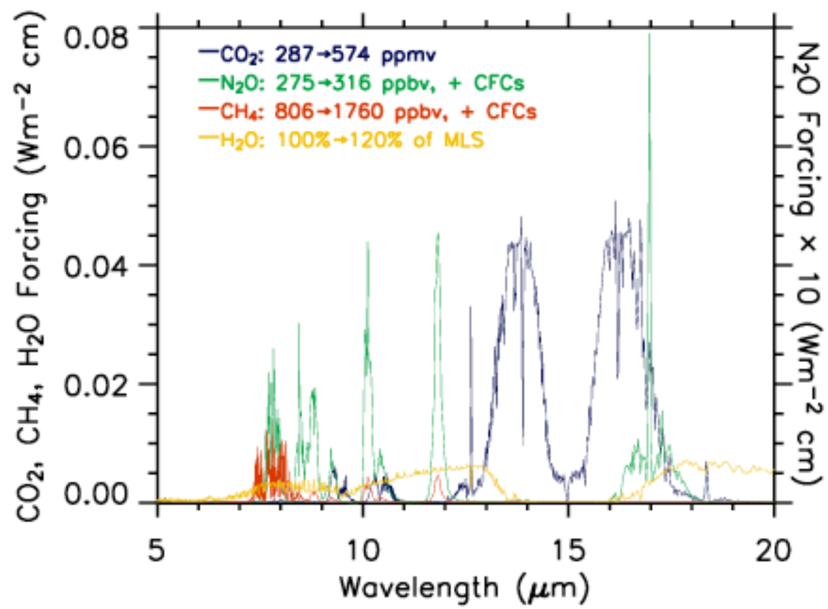
- Models should simulate this forcing as accurately as possible
- Probability that historical forcing > 0 is very likely (90%+).
- Confidence in aerosol forcing estimates is higher than in the TAR..
- The LLGHG forcing has increased by 7% to 2.59 ± 0.26 W m^{-2}

Longwave radiative forcing: Tropopause

Transmission



Forcing

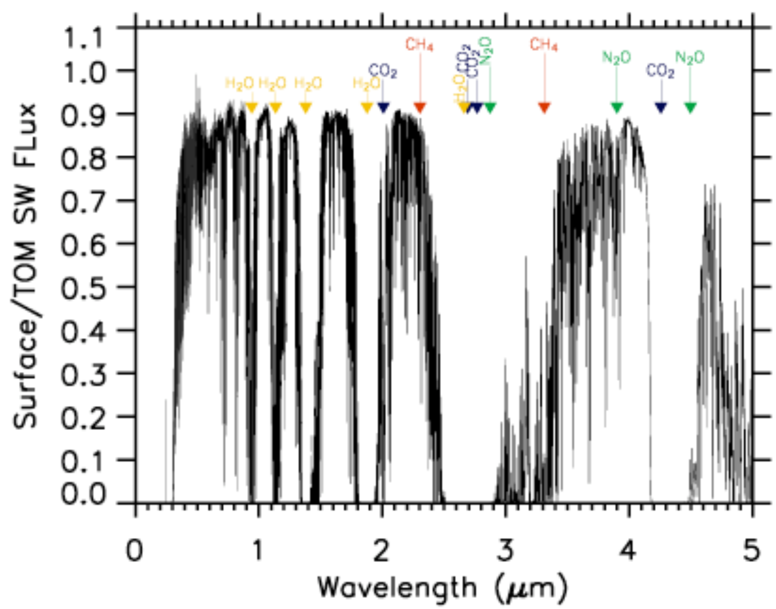


Largest forcings are at wavelengths outside the centers of absorption bands.

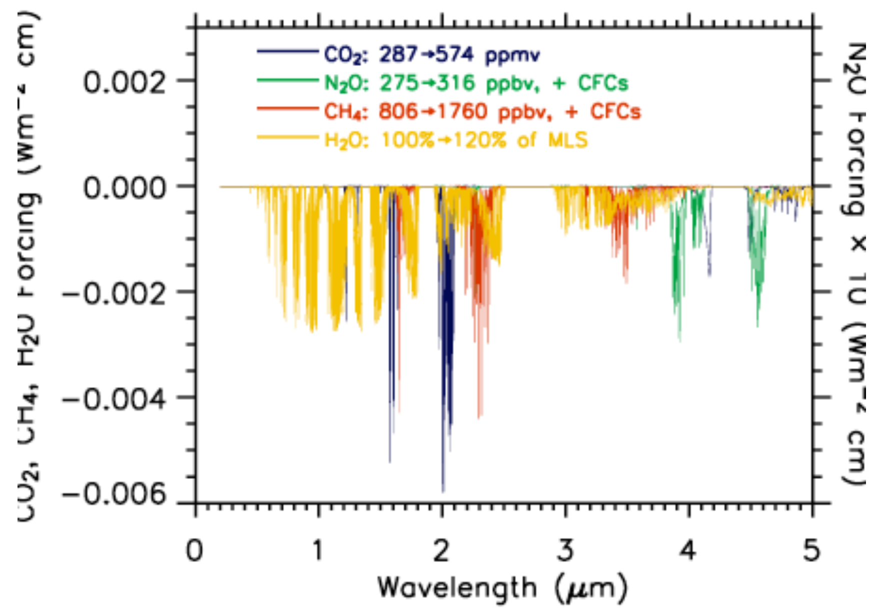
Collins et al, 2006

Shortwave radiative forcing: Surface

Transmission



Forcing



Shortwave forcings decrease the amount of sunlight reaching the surface.

Collins et al, 2006

Radiative Forcing and Climate Sensitivity

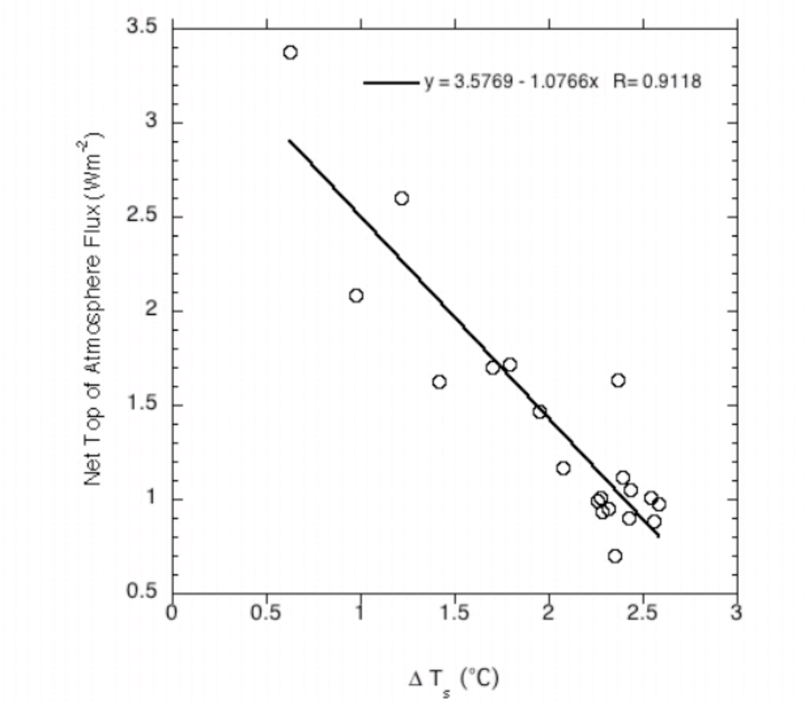


Figure 1. Change in net forcing (Wm^{-2}) at the model top versus change in surface temperature (°C) from the T42 CAM3 slab ocean model simulation for doubled CO_2. Each data point is the annual mean value from the first 20 years of the simulation.

Kiehl et al, 2006

Climate forcing and response are related by:

$$\Delta Q = \lambda \Delta T_s + \Delta F$$

with

$\Delta Q =$ radiative forcing from higher GHGs, etc.

$\lambda =$ climate sensitivity

$\Delta T_s =$ change in surface temperature

$\Delta F =$ change in climatic heat storage

Are ΔQ estimated with climate models accurate?

Link between Changing Rainfall and Temperature

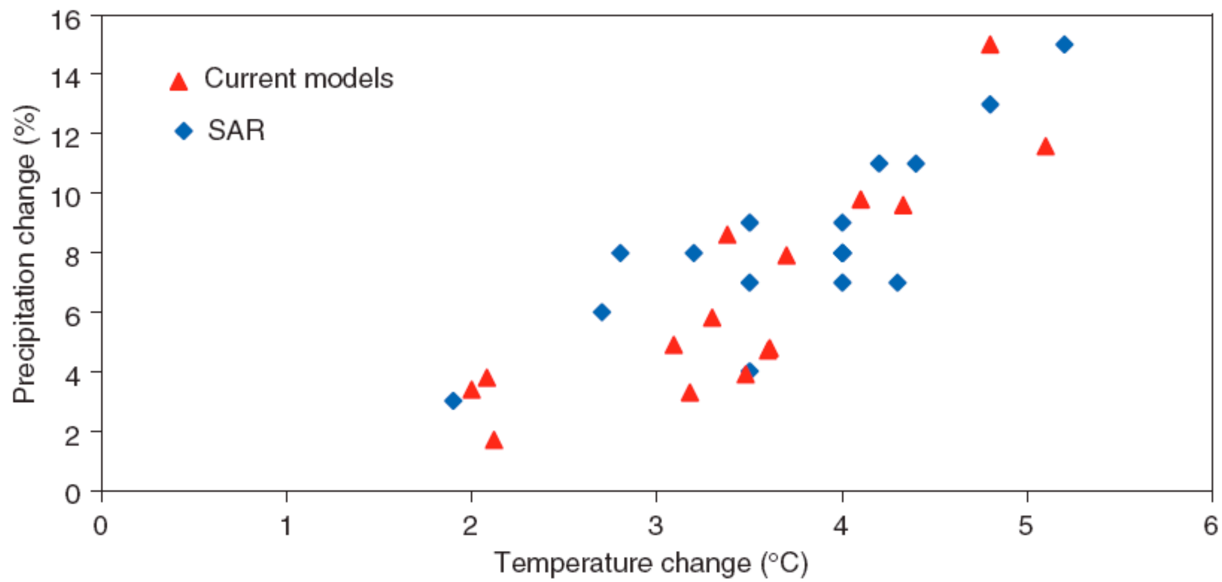


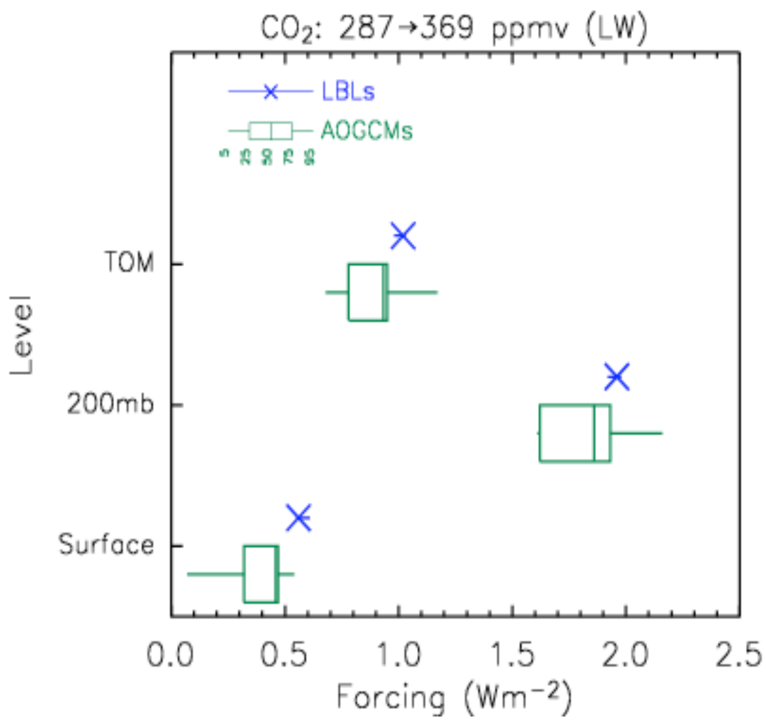
Figure 9.18: Equilibrium climate and hydrological senstitivies from AGCMs coupled to mixed-layer ocean components; blue diamonds from the SAR, red triangles from models in current use (LeTreut and McAvaney, 2000 and Table 9.1).

IPCC TAR, 2001

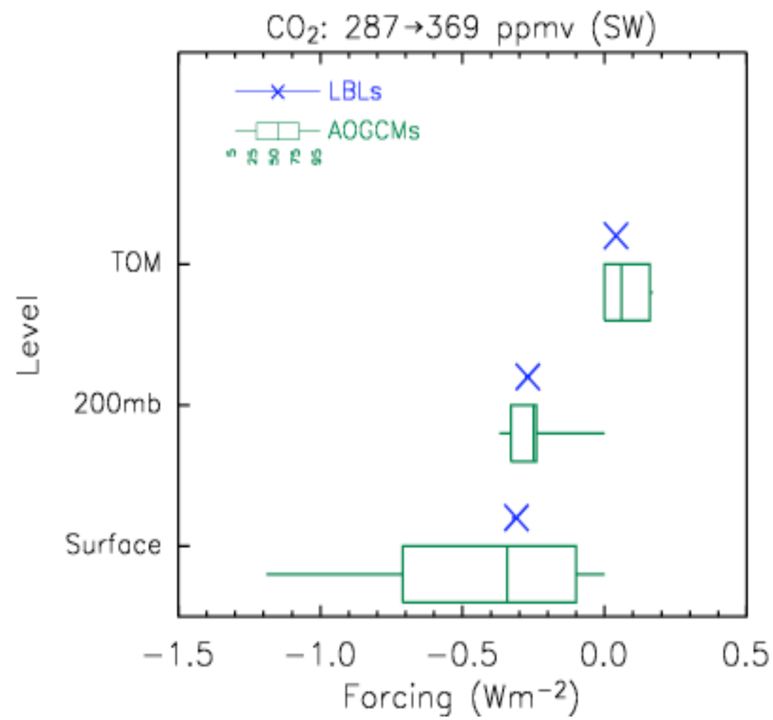
Uncertainties in forcing affect not only temperature but also the hydrological cycle.

Forcing by historical increase in CO_2

Longwave



Shortwave

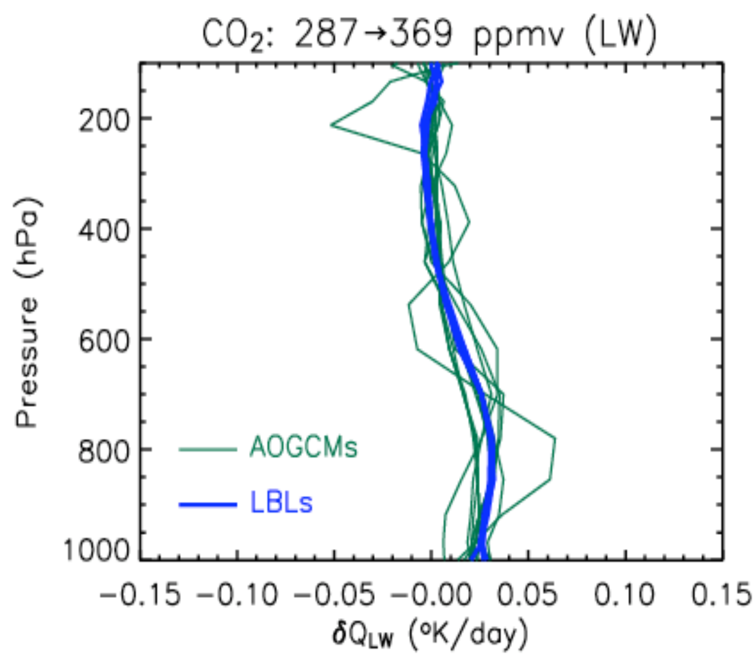


Longwave: Relative difference is 8% at 200hPa and 33% at surface.
Shortwave: Large range in surface forcing: RMS / mean = 0.94

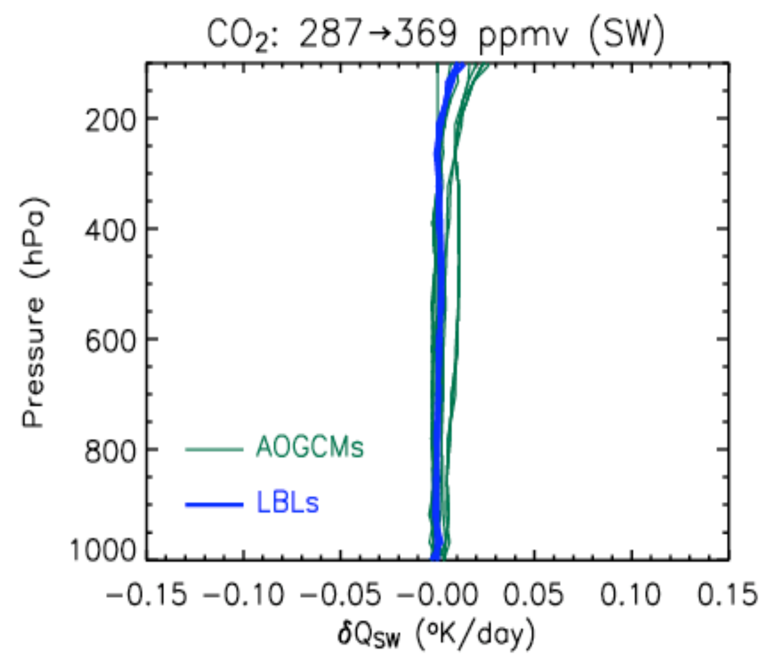
Collins et al, 2006

Change in heating rates by CO_2

Longwave



Shortwave

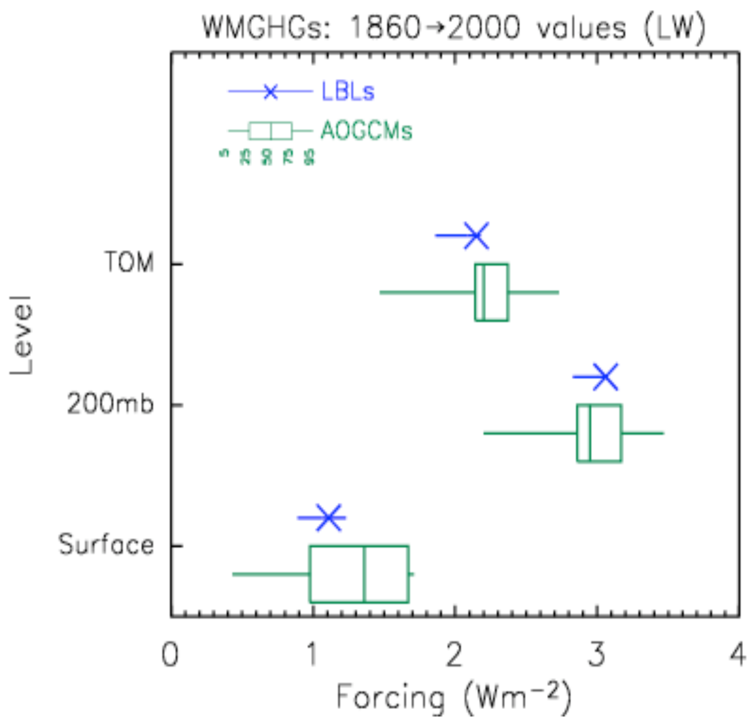


Longwave: Most models agree in magnitude and sign of the additional heating.
Shortwave: Average model agrees in magnitude and sign of the additional heating.

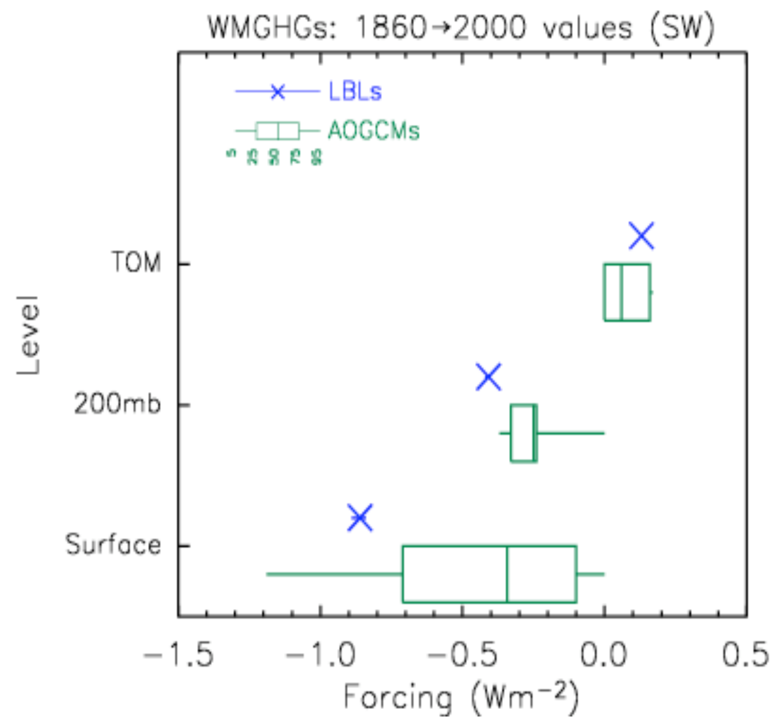
Collins et al, 2006

Forcing by historical increase in GHGs

Longwave



Shortwave



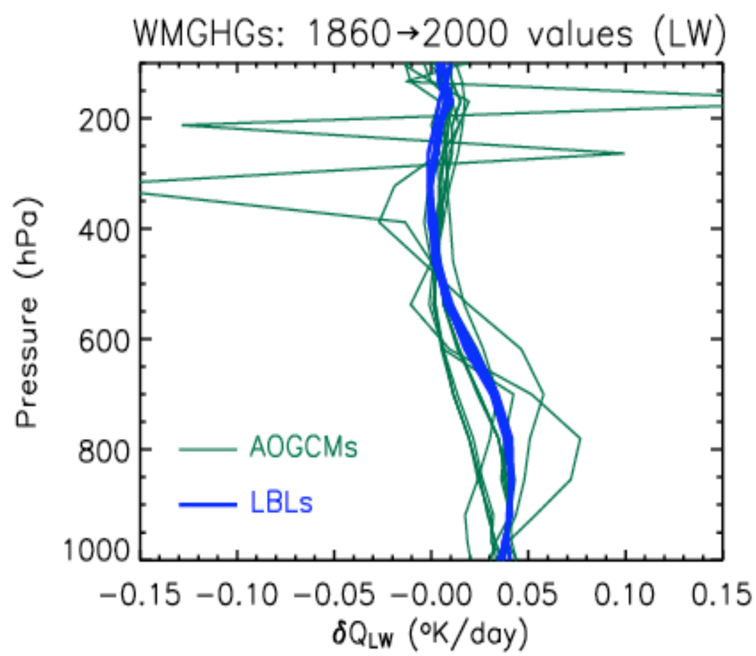
Longwave: None of the differences are statistically significant.
Shortwave:All of the differences are statistically significant.

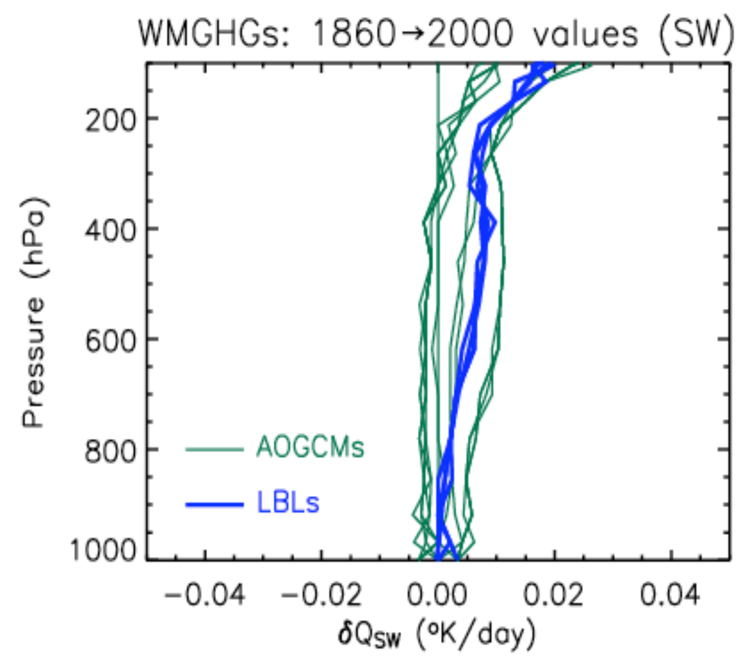
Collins et al, 2006

Change in heating rates by WMGHGs

Longwave

Shortwave

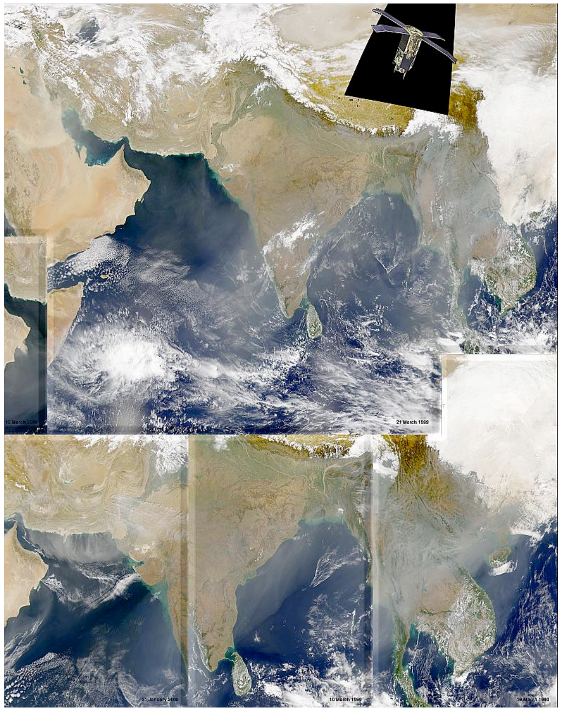




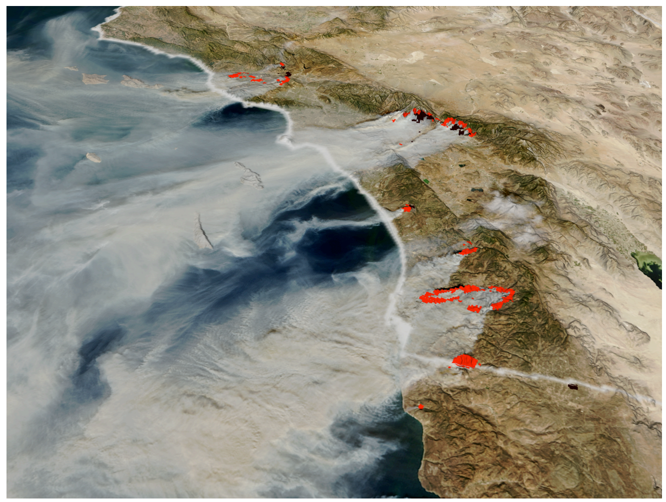
Longwave: Some models show evidence of numerical artifacts.
Shortwave:Some models produce tropospheric cooling, an error in sign.

Collins et al, 2006

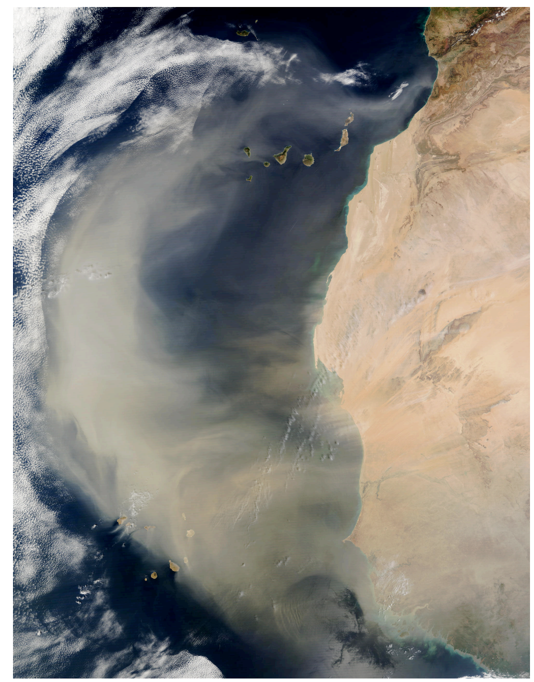
Natural and anthropogenic aerosols



India, March 2000

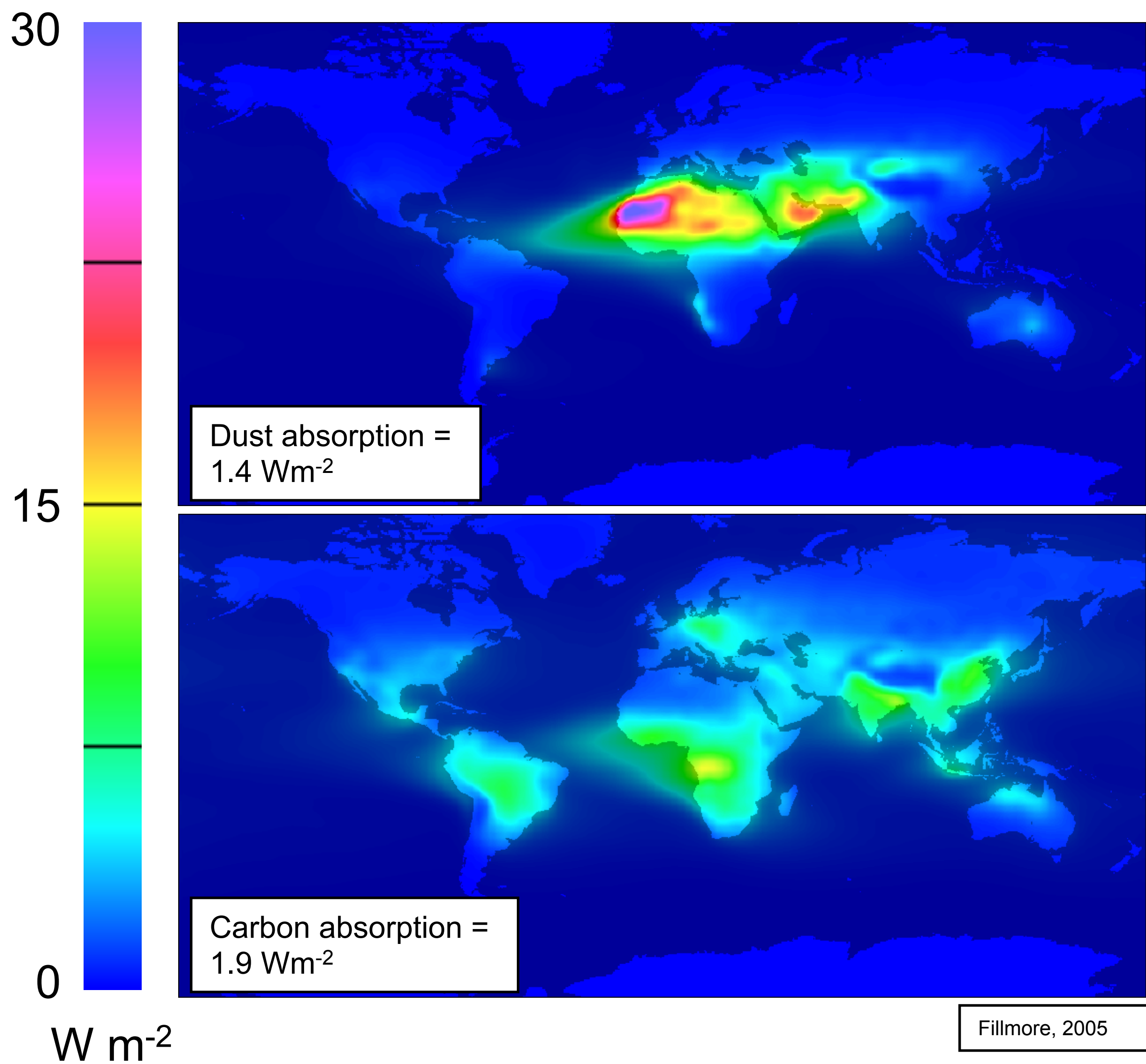


California, October 2003



Africa, March 2003

Magnitude of aerosol absorption



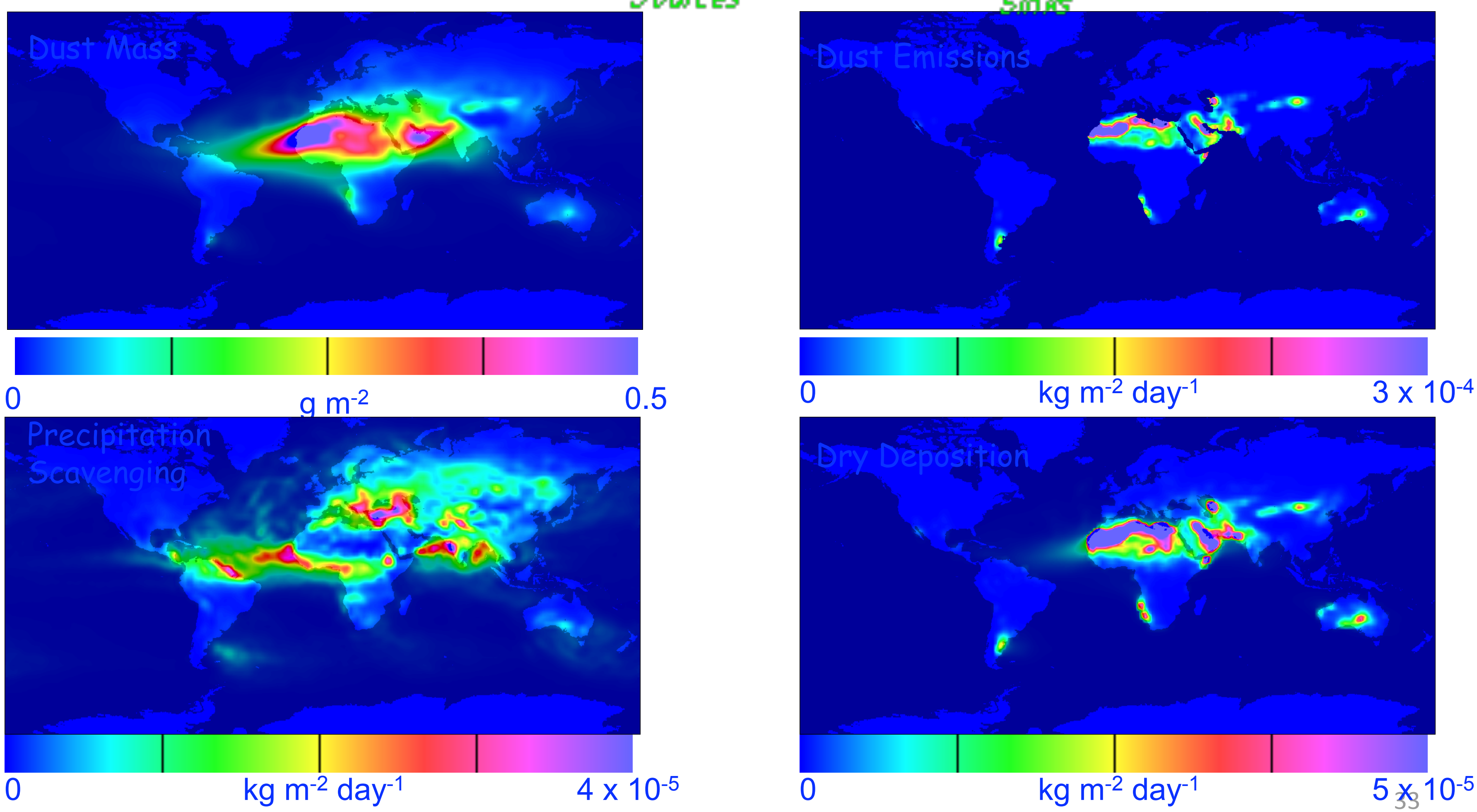
Fillmore, 2005

Gas	Absorption
CO_2	1
O_2	2
O_3	14
H_2O	43

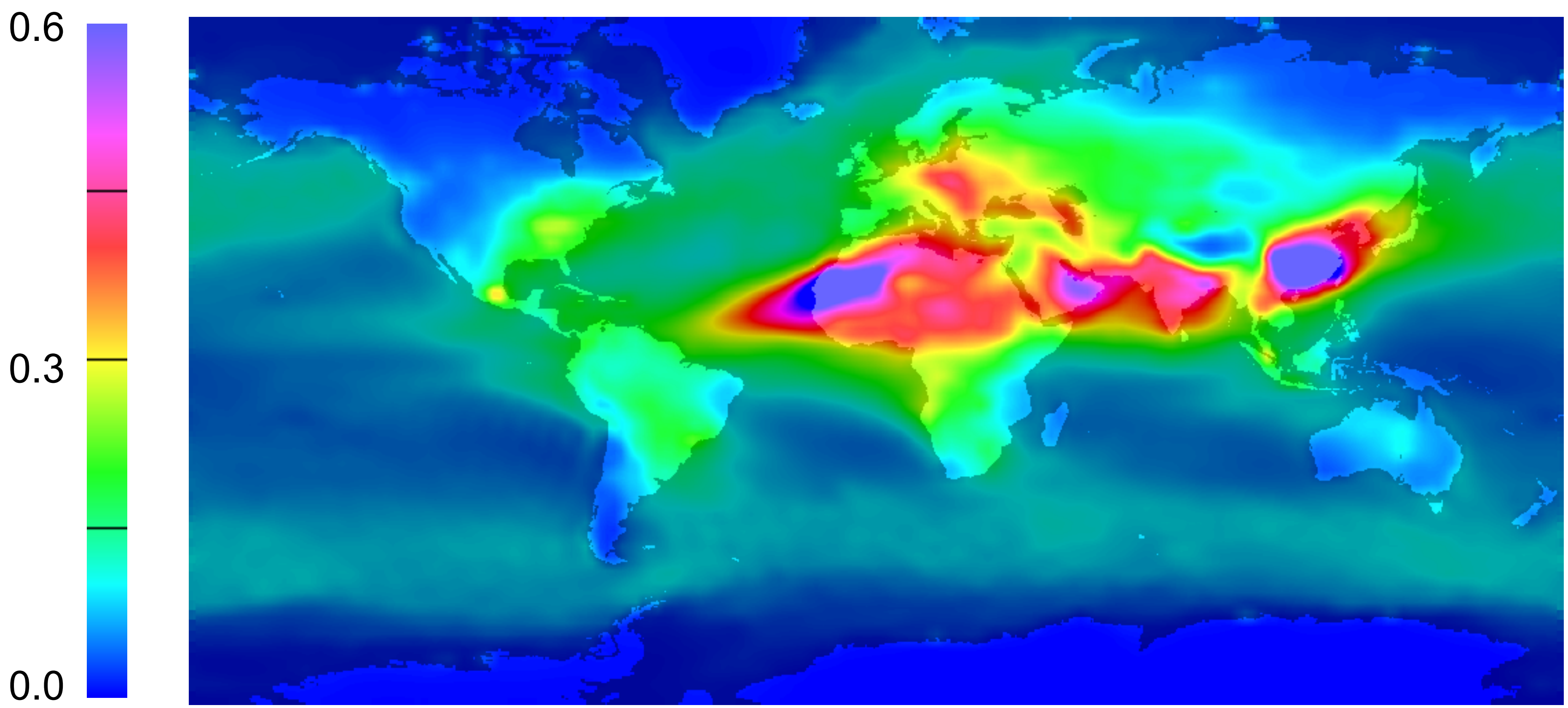
- Collectively, aerosols are 3rd most significant absorber.

Chemical Transport Models

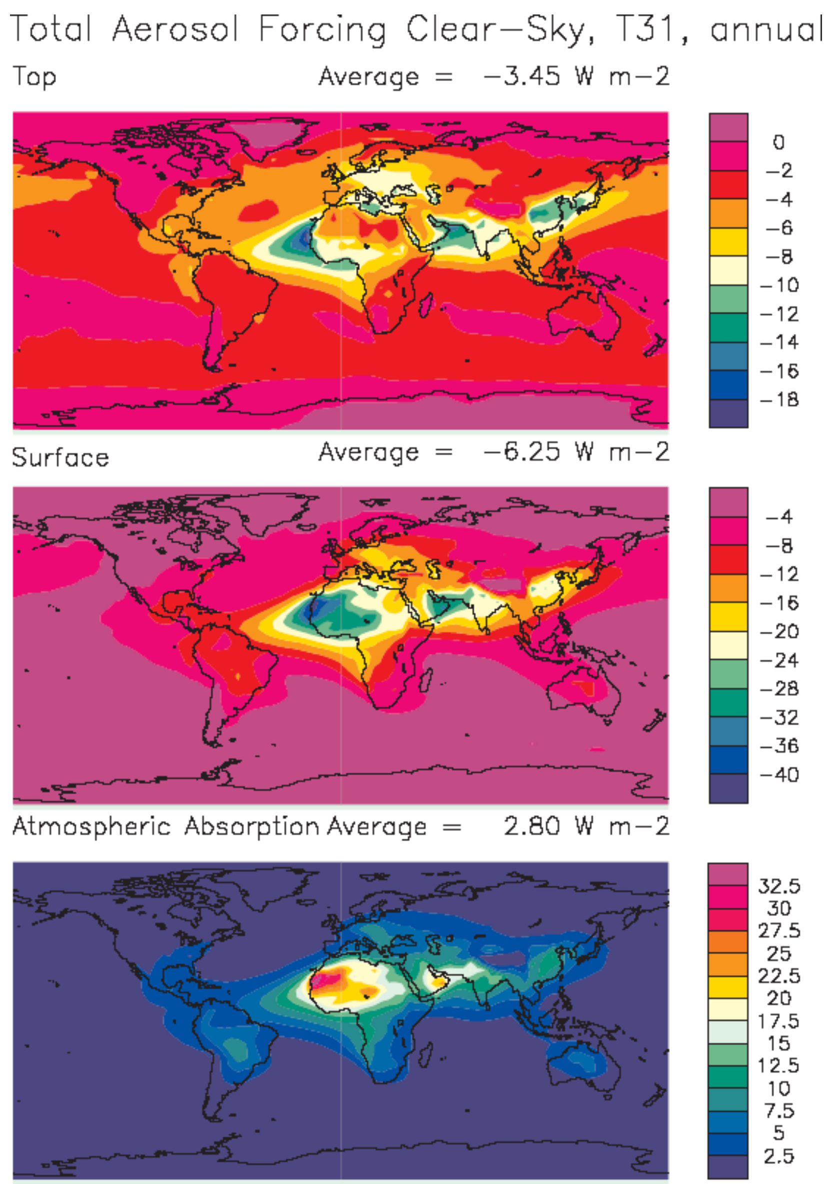
$$\frac{\partial q_i}{\partial t} + \nabla \cdot (q_i \vec{v}) = \underbrace{S_{emis} + S_{chem}}_{\text{Sources}} \underbrace{- \tilde{S}_{wet} - \tilde{S}_{dry} - \tilde{S}_{chem}}_{\text{Sinks}}$$



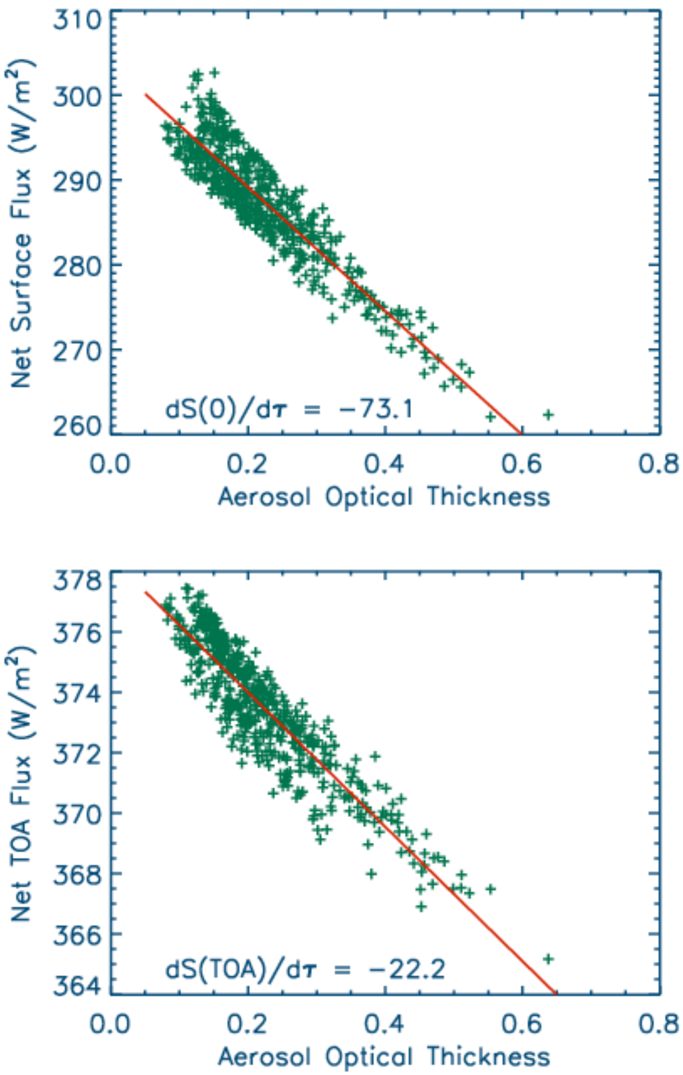
Simulated aerosol optical depth

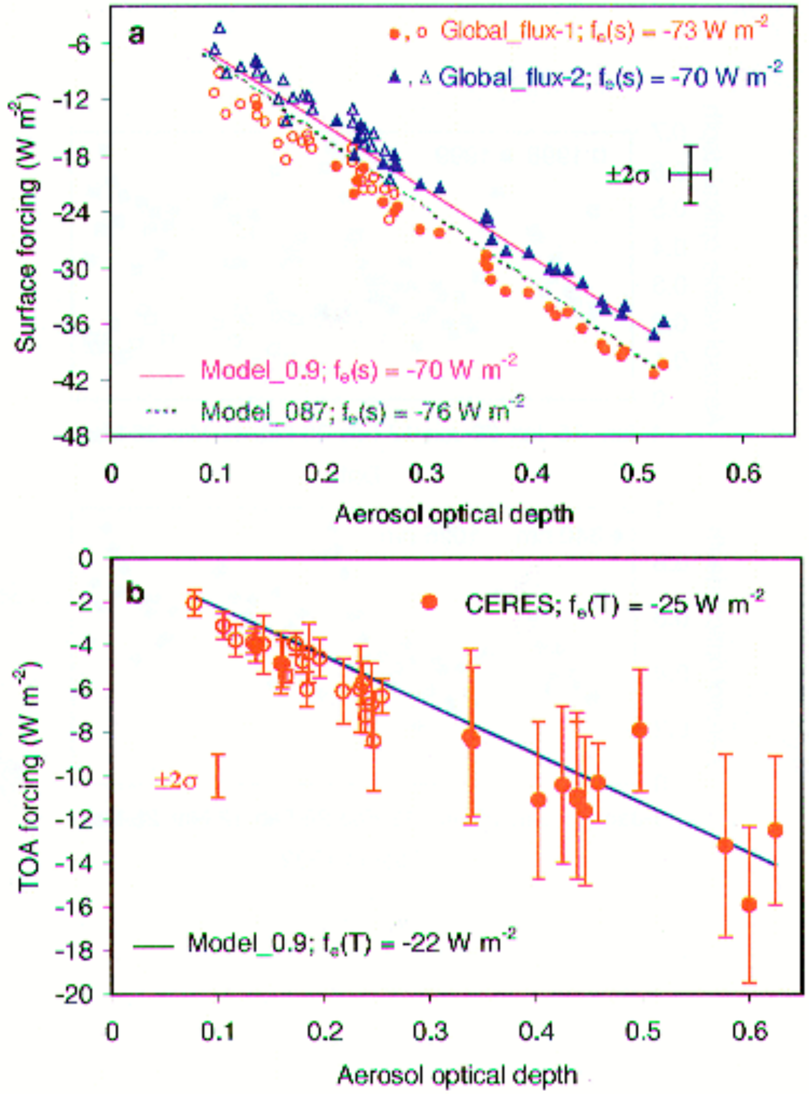


Total Clear-sky Aerosol Forcing

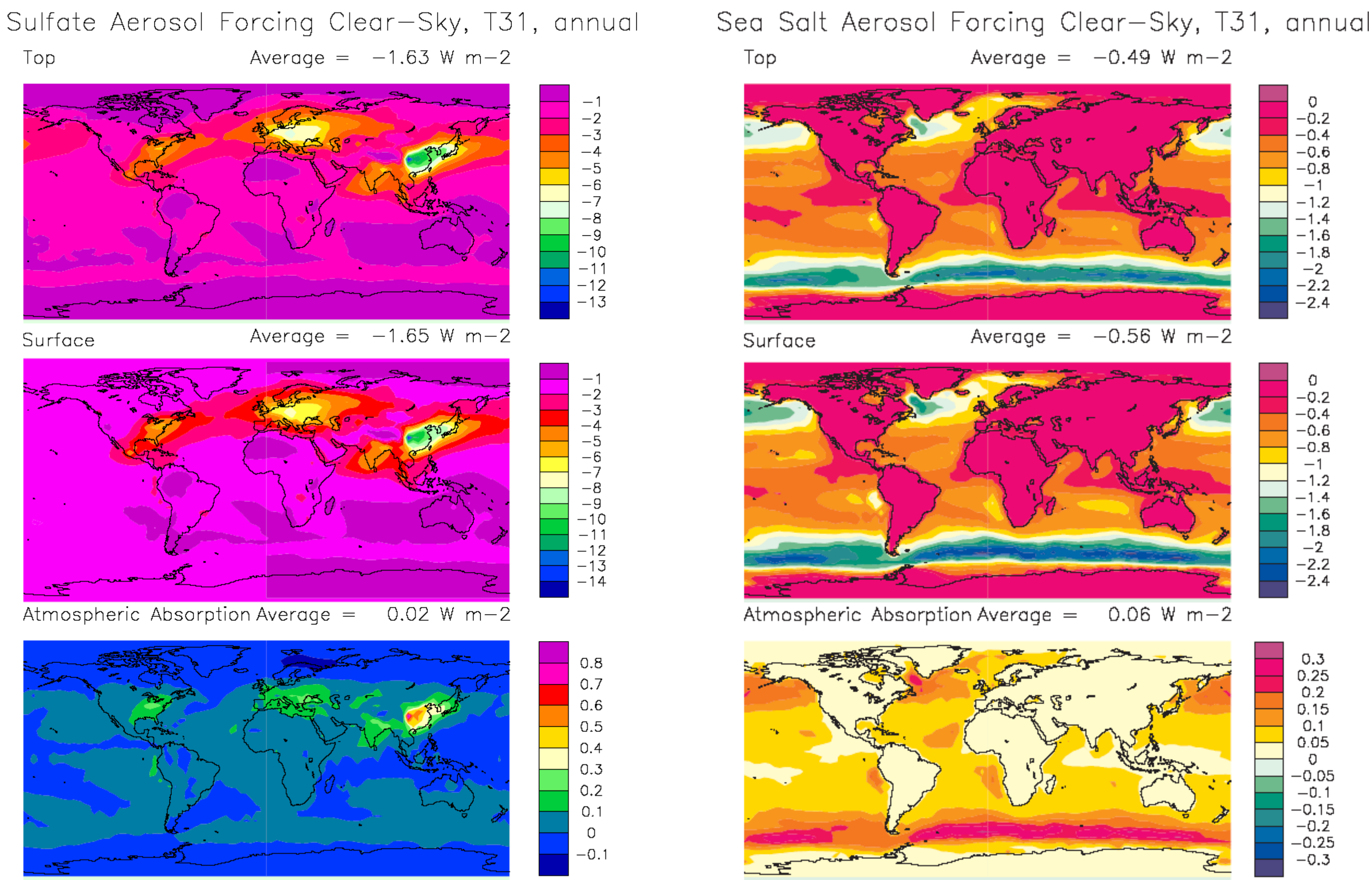


Relationship of optical depth and forcing

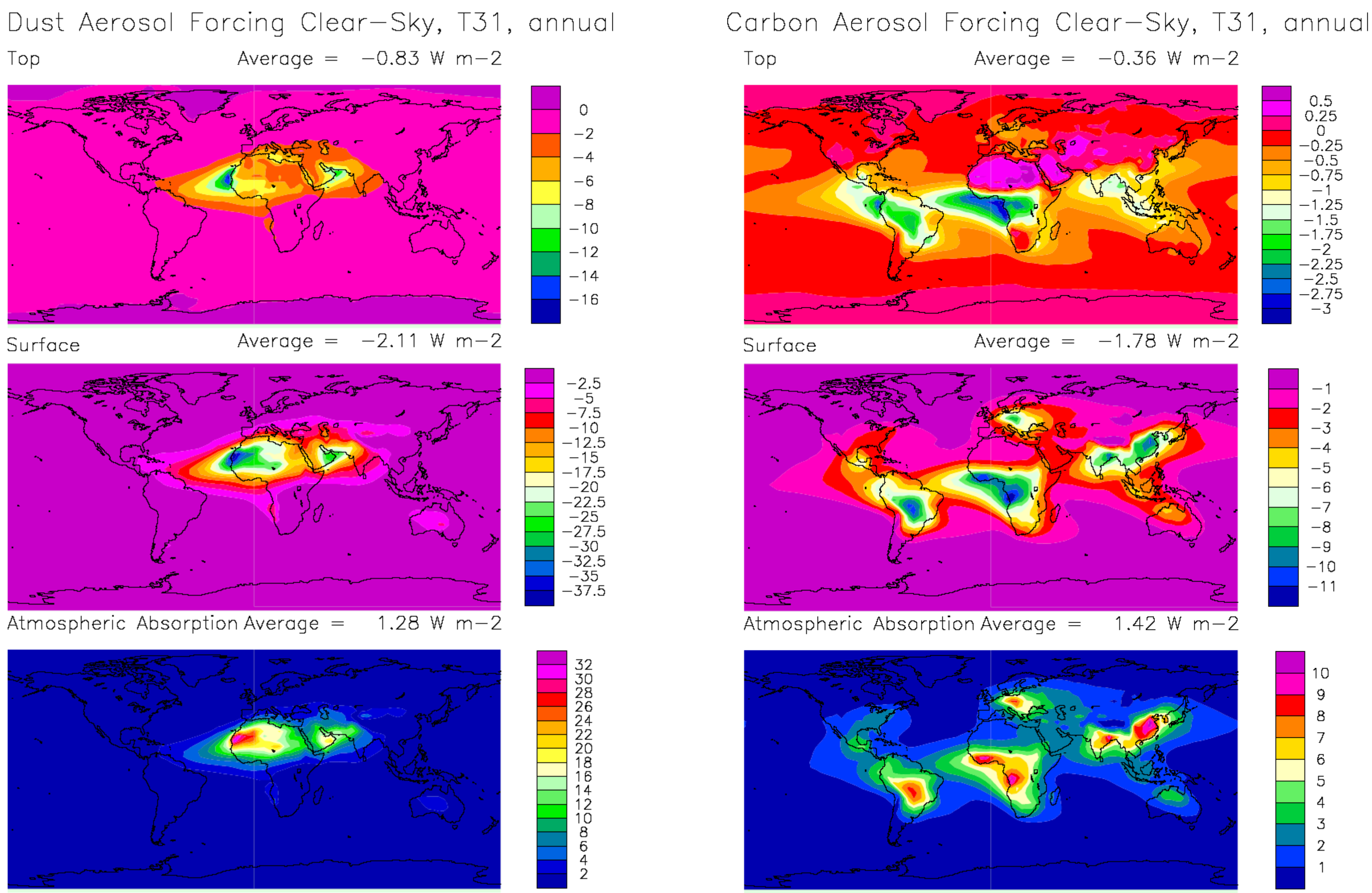




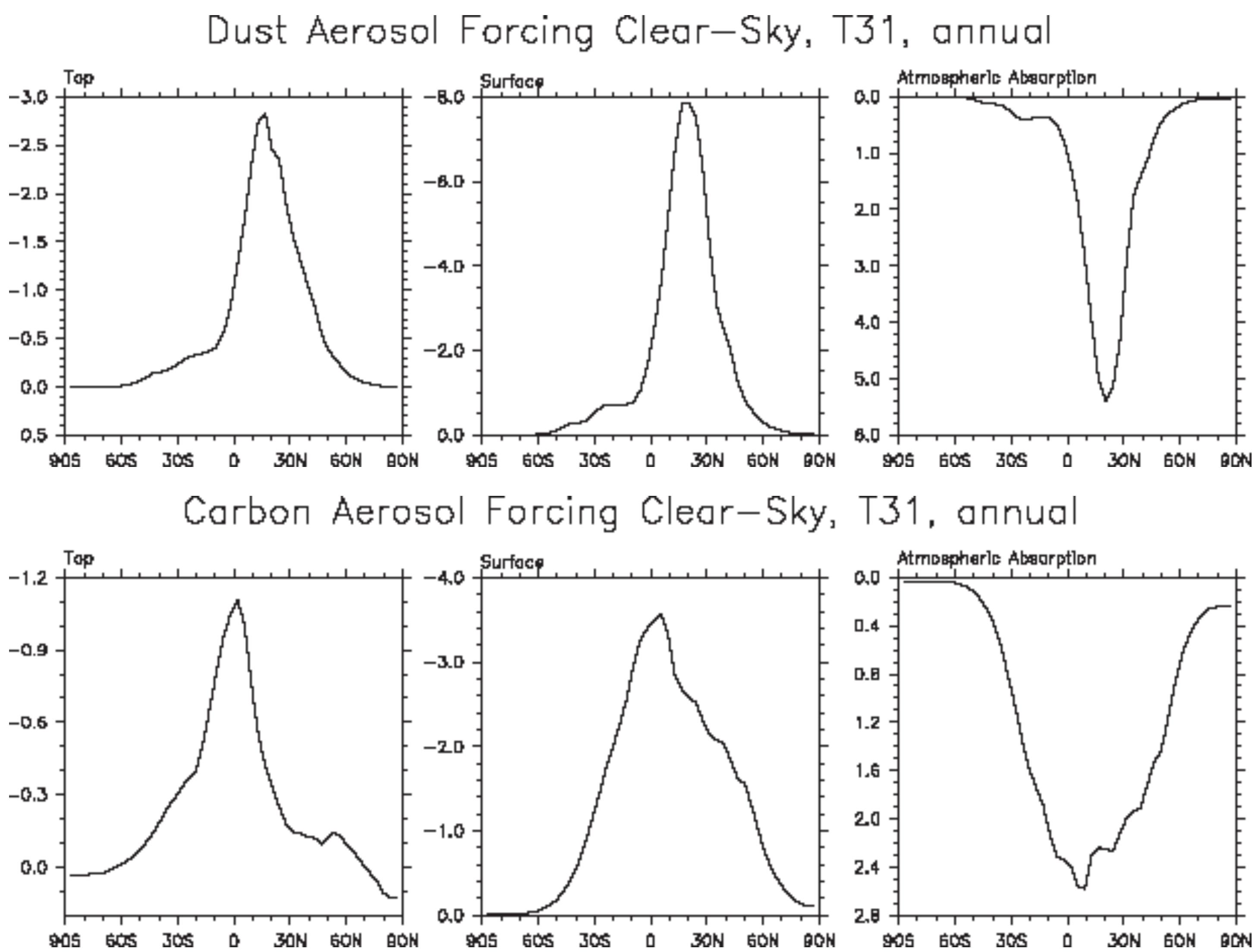
Clear-sky Forcing by Sulfate and Sea-Salt



Clear-sky Forcing by Dust and Carbon



Meridional Distribution of Absorption



Current CAM radiation treatment

- RRTMG is default RT method for CAM & CCSM

- Developments last AMWG meeting:
  - Completion of integration of RRTMG with CAM
  - Development of optics for clouds and aerosols
  - Science tests to understand OLR bias for clear skies

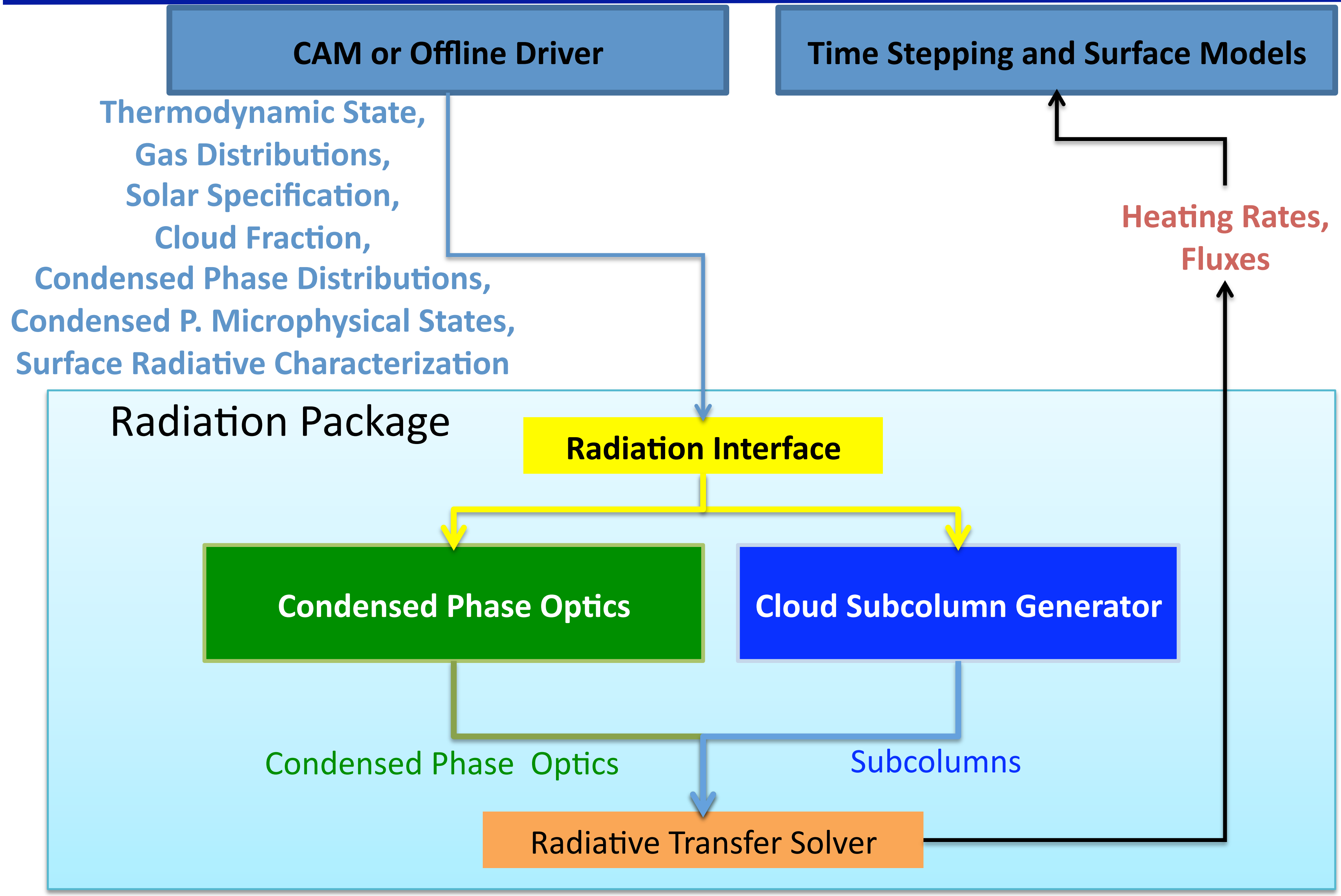
Condensed phase optics

1. All new optics are designed for RRTMG

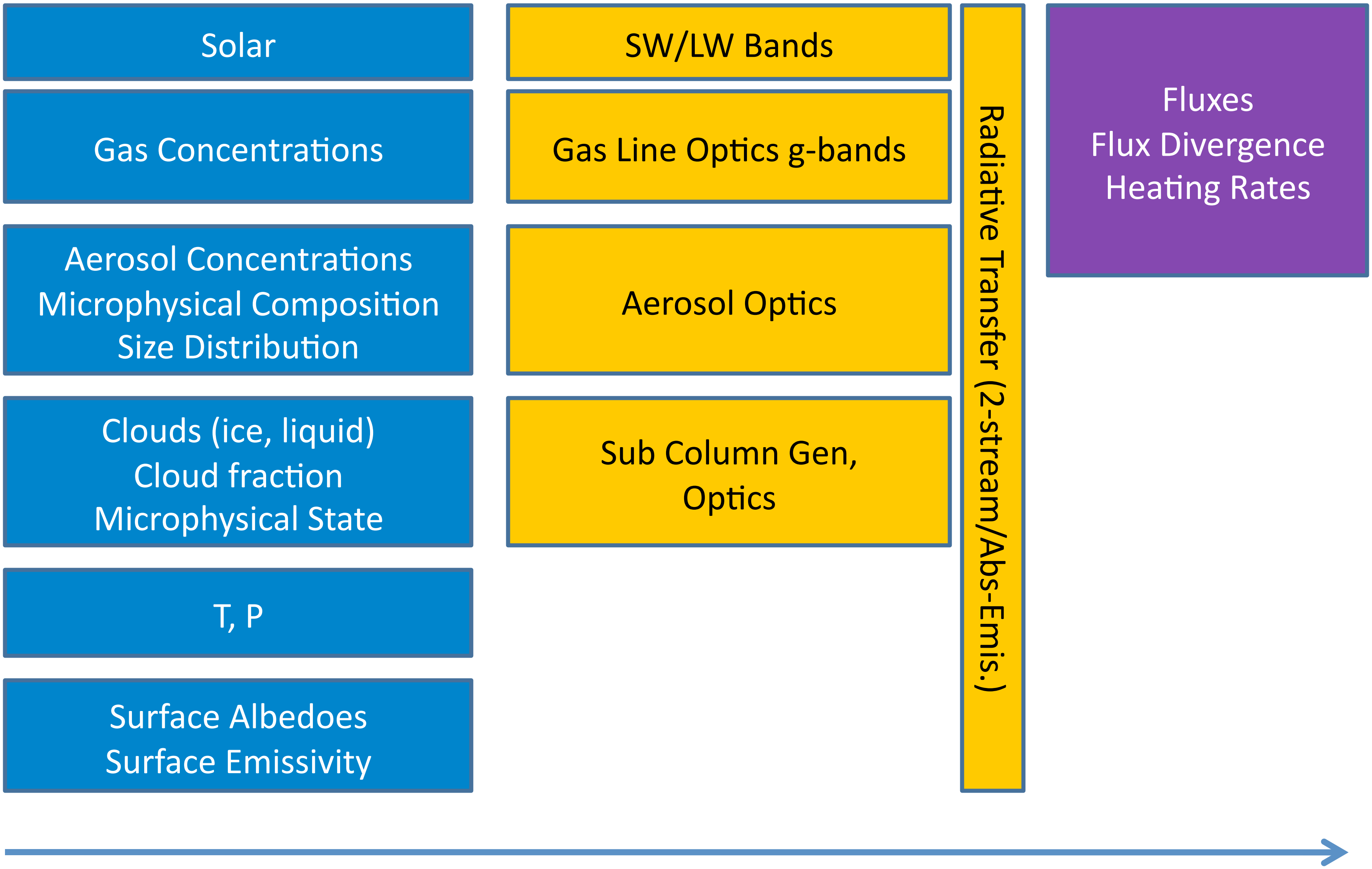
2. Cloud optics
   - Liquid cloud (MG μphysics): Conley optics
   - Ice cloud (MG μphysics): Mitchell optics

3. Aerosol optics
   - Bulk aerosol model: Ghan optics
   - Modal aerosol model: Ghan optics

Schematic of new radiation

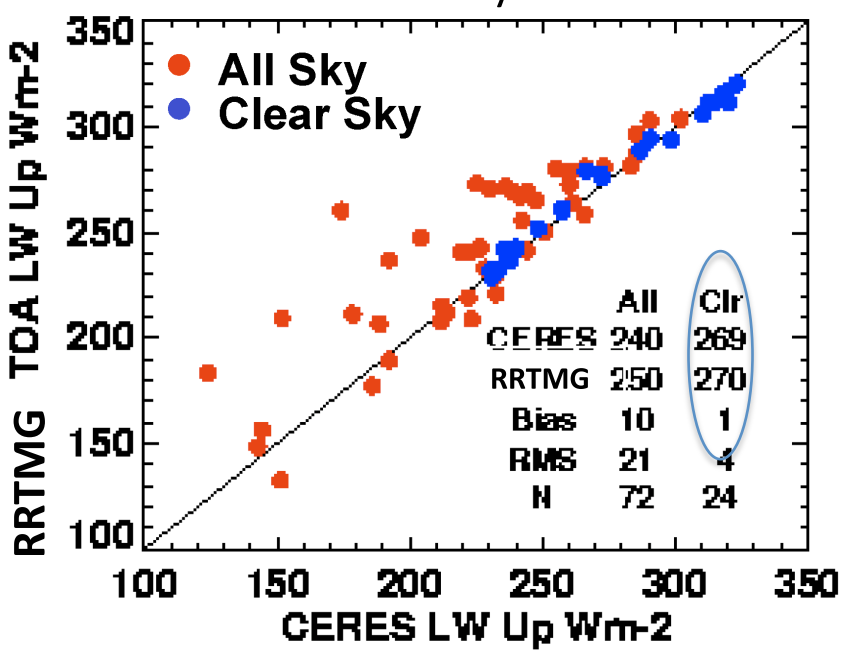


Radiative Inputs and Outputs

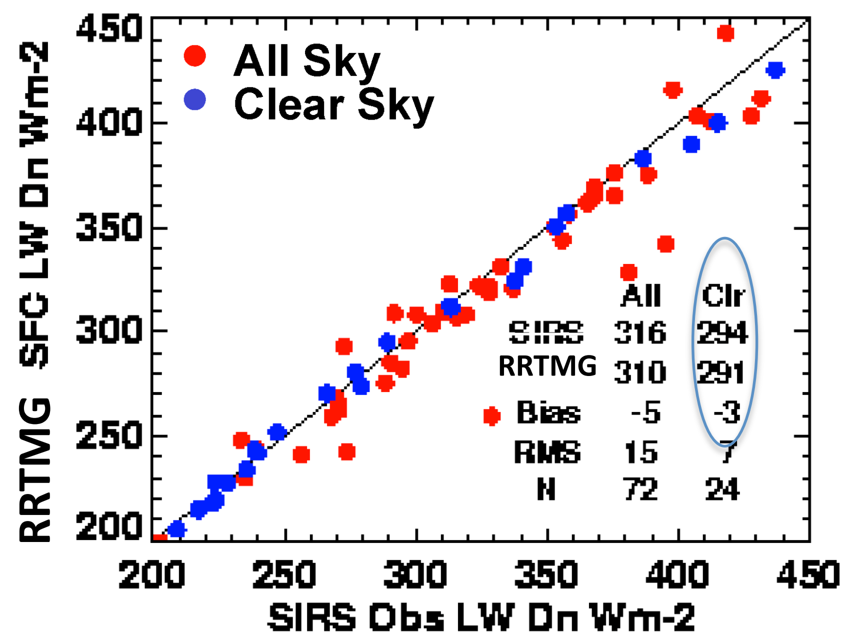


Evaluation using ARM & CERES

TOA Clear-Sky OLR



Surface Clear-Sky Flux



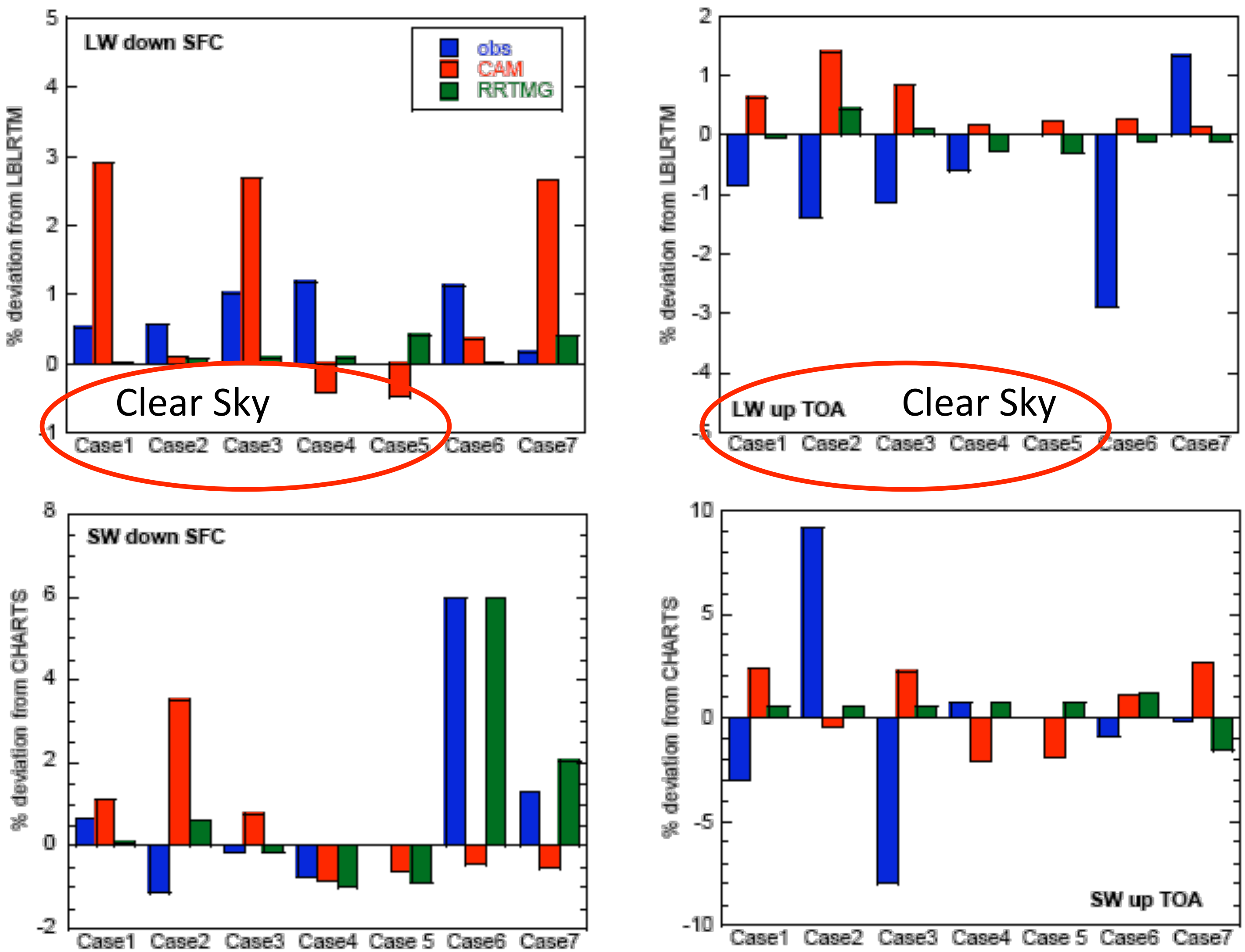
1 W/m² error relative to CERES

-3 W/m² error relative to ARM

Based on Observed Profiles

Dave Rutan and Tom Charlock (NASA)

RRTMG vs. LBL Benchmarks



Errors in RRTMG are <1% relative.

Based on Observed Profiles

Lazaros Oreopoulos (NASA Goddard)

Development goals for 2009

- Introduce solar spectral variability (IPCC)
- Introduce volcanic radiative forcing (IPCC)
- Adapt MAM to new radiation framework
- Develop (multi-) Column Radiation Model
- Self-consistent treatment of upper atmosphere
- Integrate RRTMG with WACCM
- Study climatic effects of new radiation package

Goals of the
Radiative Transfer Model Intercomparison Project (RTMIP)

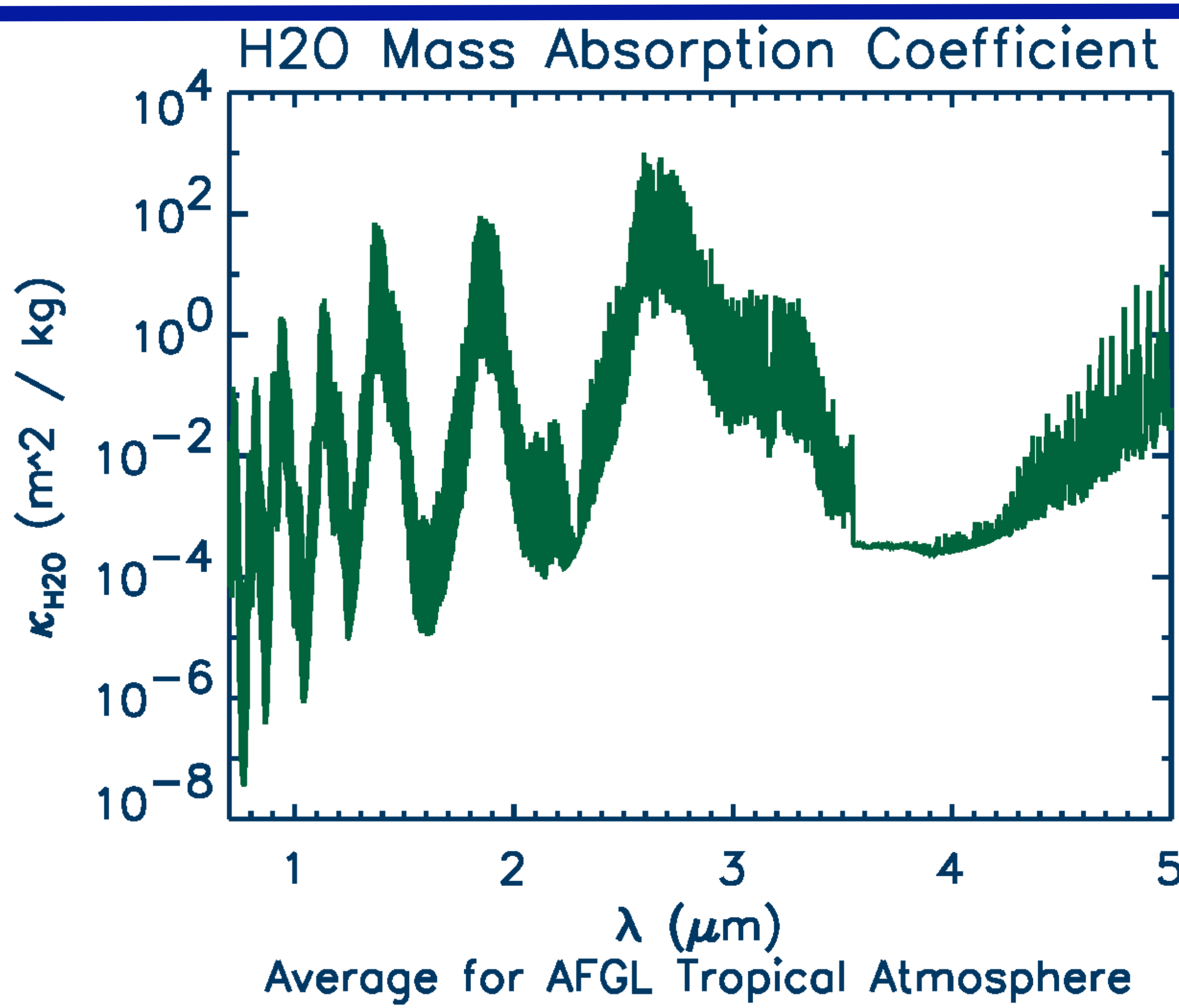
- Determine differences among models in idealized conditions

- Compare forcing by well-mixed GHGs from:
  - *GCMs participating in the IPCC AR4*
  - *Line-by-line (LBL) codes: benchmarks*

- Determine accuracy of GCM codes under idealized conditions.

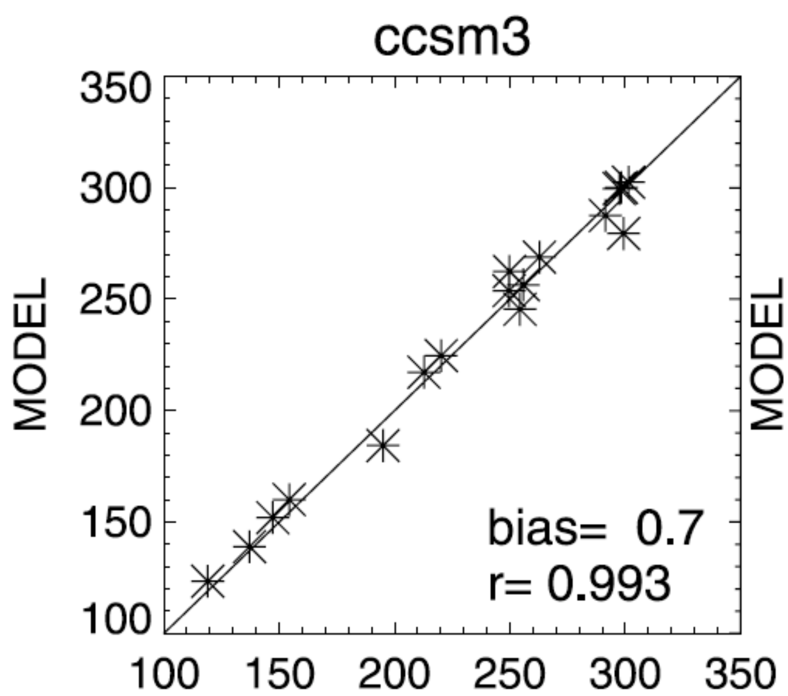
- Types of forcing considered:
  - *Present-day - preindustrial changes in WMGHGs*
  - *2×CO_2 - 1×CO_2 and 4×CO_2 - 1×CO_2*
  - *Combinations of increased CH_4, N_2O, and CFCs*
  - *Feedbacks from increased H_2O*

Absorption Cross-Section of H_2O



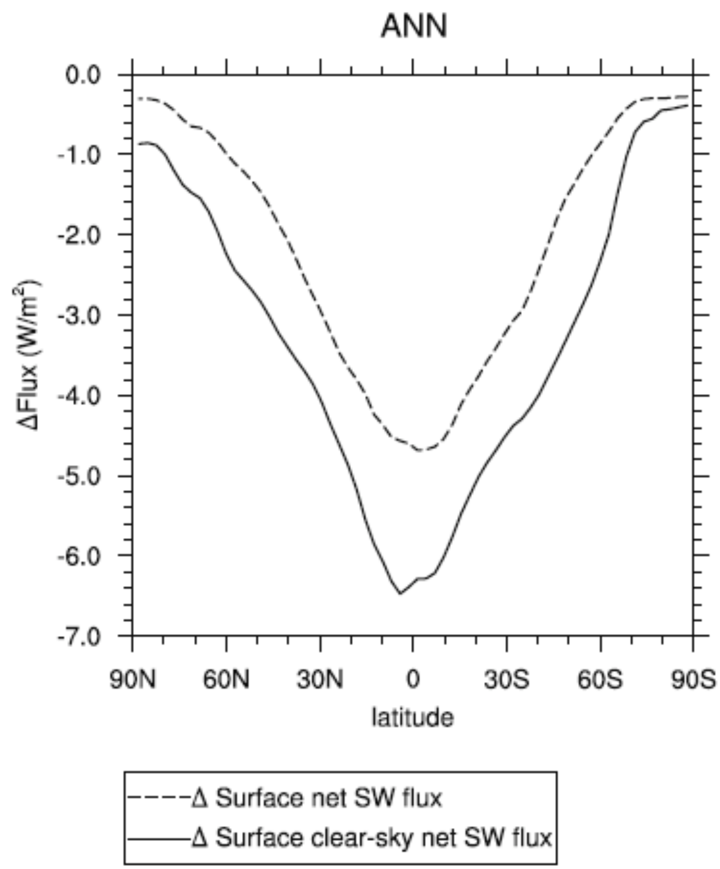
Improved Surface Shortwave Fluxes

Model vs. Surface Radiometers



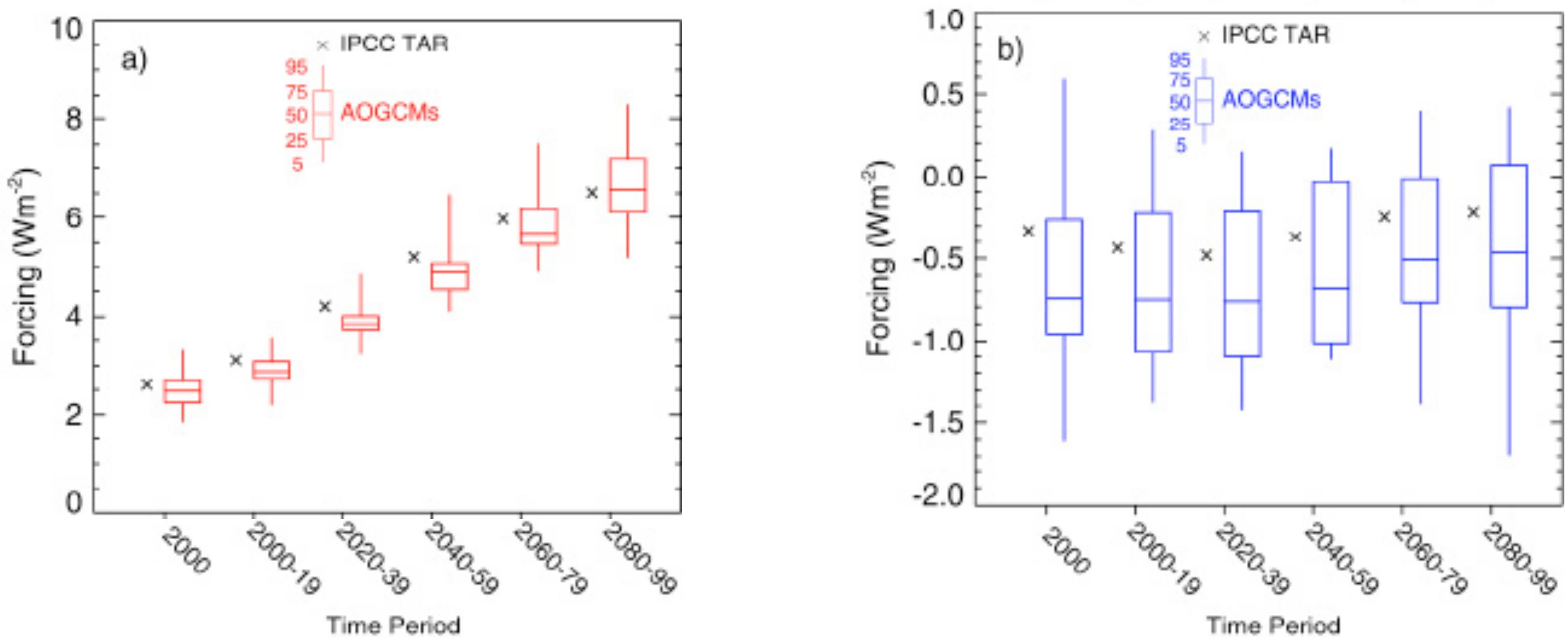
Wild et al, 2006

Effect of Updating H2O Spectroscopy



Collins et al, 2006

Radiative Forcing for the A1B SRES Scenario: 20 AOGCMs



IPCC AR4, 2007

Summary for longwave forcing:

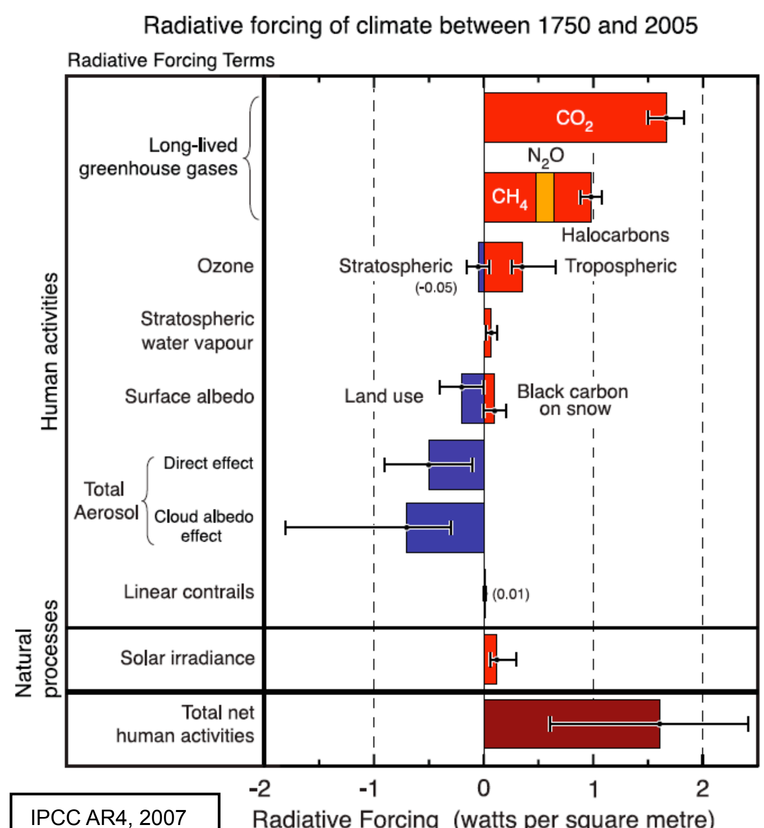
- At 2000, median model & IPCC differ by only -0.13 W m^{-2}.
- By 2100, range in forcing is 3.1 W m^{-2}, or 47% of mean.

Summary for shortwave forcing:

- Modeled forcing spans 0 Wm^{-2} in every 20-year period.
- By 2100, forcing ranges from –1.7 W m^{-2} to +0.4 W m^{-2}.

Contribution of aerosols to climate forcing

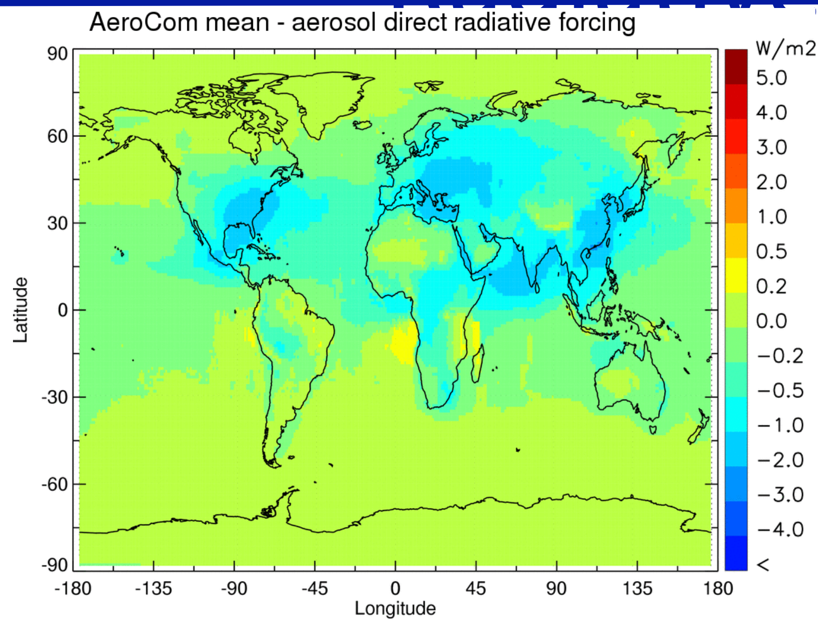
Radiative forcing is an "externally imposed perturbation in the radiative energy budget of the Earth's climate system." (IPCC TAR)

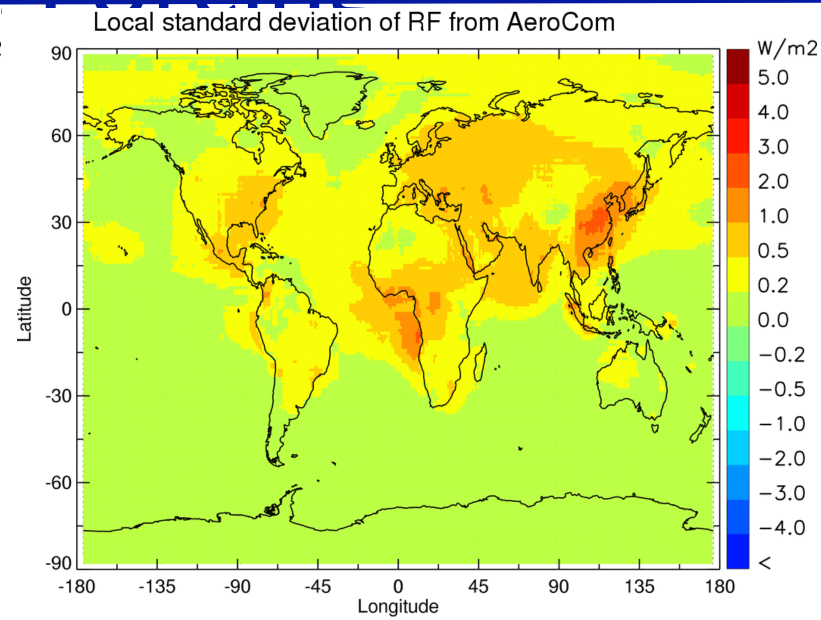


IPCC AR4, 2007

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

Model Estimates of Aerosol Radiative Forcing

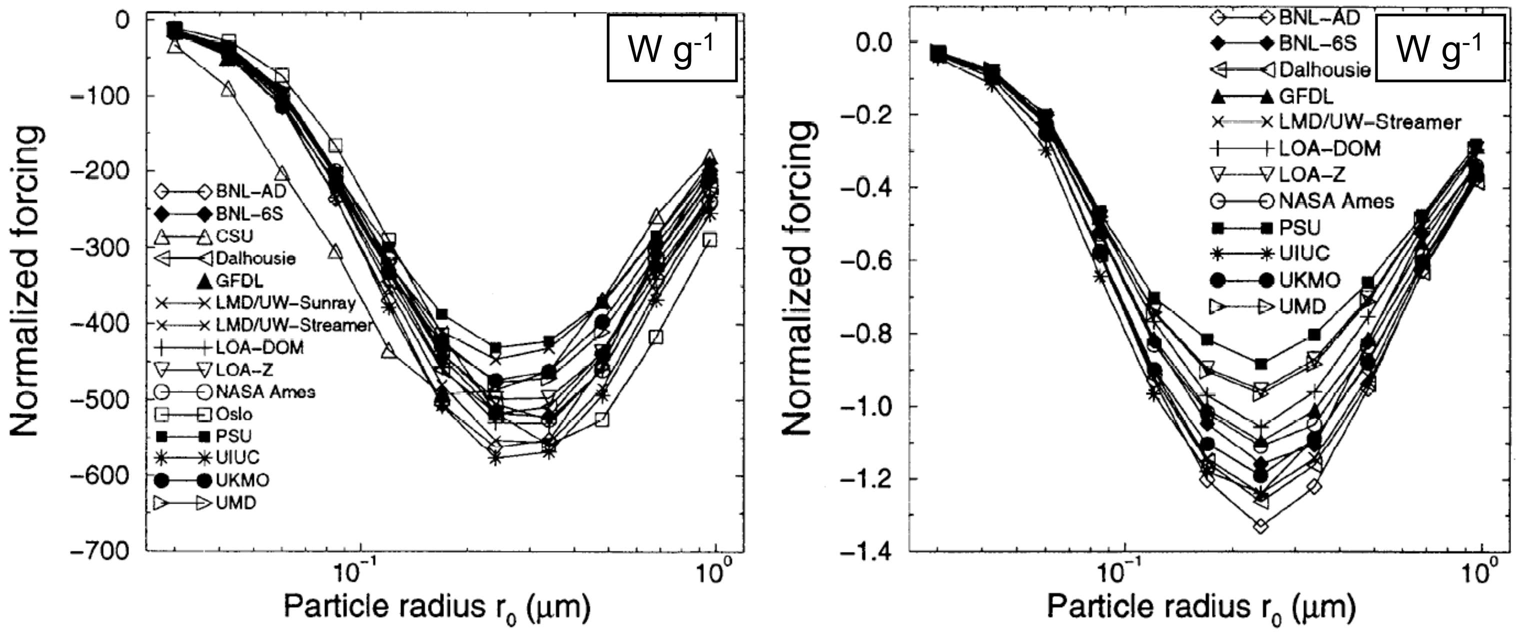




IPCC AR4, 2007

Species	Forcing (**W m^{-2}**)
Sulfate	–0.4 ± 0.2
Fossil fuel organic carbon	–0.1 ± 0.1
fossil-fuel black carbon	+0.2 ± 0.1
Biomass burning	0.0 ± 0.1
Nitrate	–0.1 ± 0.1
mineral dust	–0.1 ± 0.2
Total	**–0.5 ± 0.4**

Uncertainty in Aerosol Forcing from Radiative Parameterizations

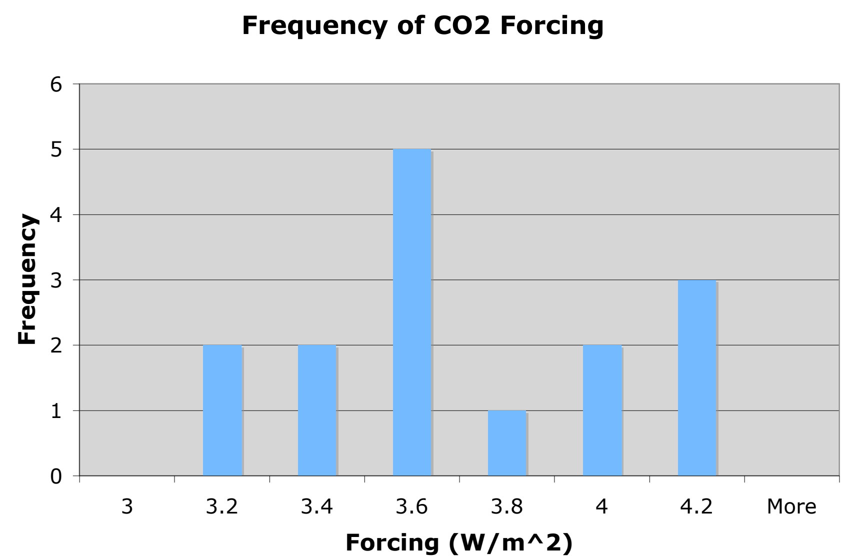


Boucher et al, 1998

- Range in forcing related to differences in radiative transfer.
- Uncertainty from differences in optics and radiation = ± 20%.
- This analysis has *not* been performed for absorbing aerosols.

Range of CO_2 Forcing from AGCM Simulations

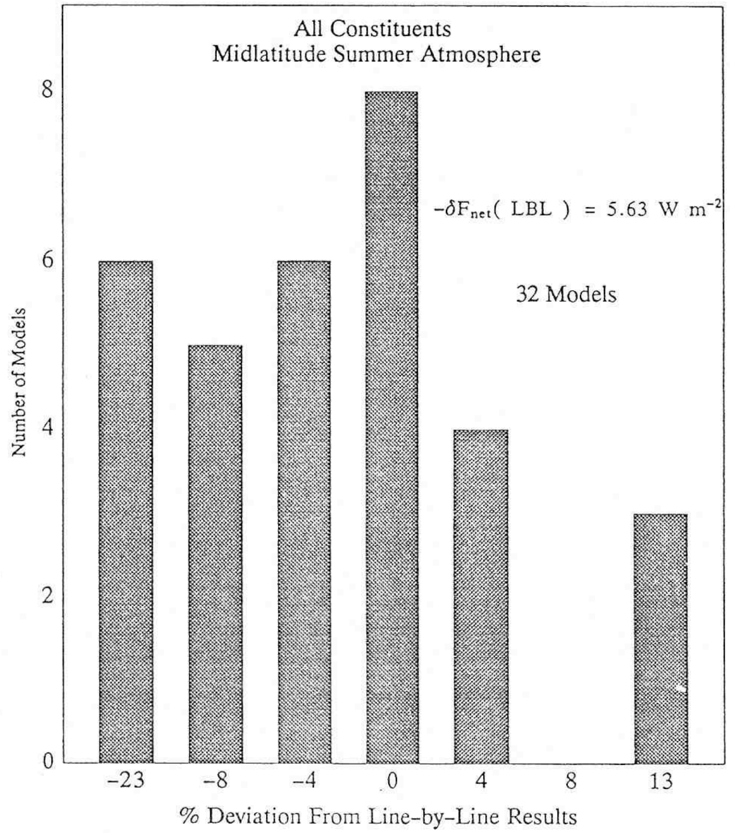
Grou p	Model	Total (W m^{-2})
CCCma	CGCM 3.1 (T47/T63)	3.32
CSIRO	CSIRO-Mk3.0	3.47
GISS	GISS-EH/ER	4.06
GFDL	GFDL-CM2.0/2.1	3.50
IPSL	IPSL-CM4	3.48
CCSR/NIES/FRCGC	MIROC 3.2-hires	3.14
CCSR/NIES/FRCGC	MIROC 3.2-medres	3.09
MPI	ECHAM5/MPI-OM	4.01
MRI	MRI-CGCM2.3.2	3.47
NCAR/CRIEPI	CCSM3	3.95
UKMO	UKMO-HadCM3	3.81
UKMO	UKMO-HadGEM1	3.78
Mean±std. deviation		**3.67±0.28**



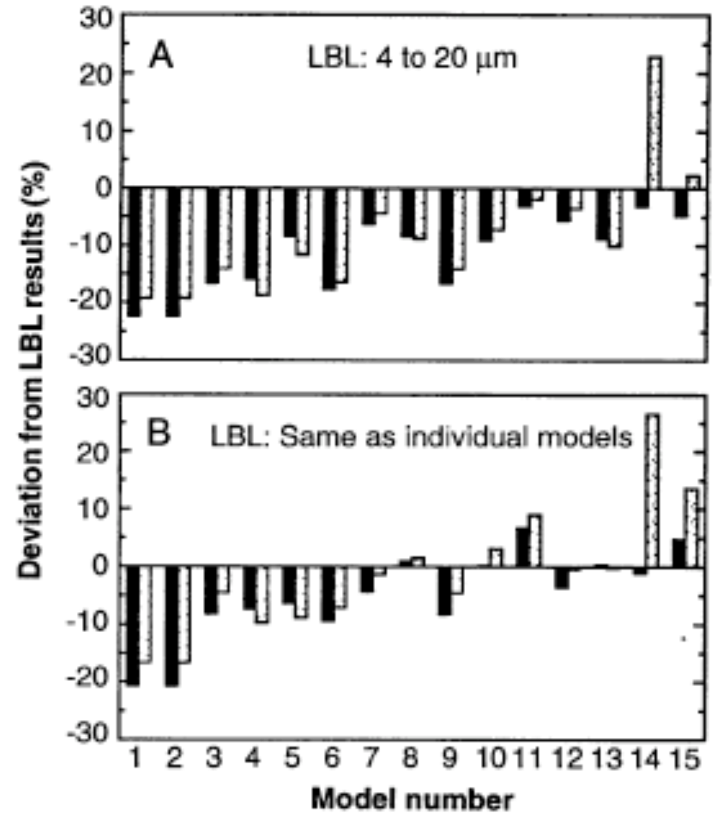
IPCC AR4, 2007

- The forcing values are for $2xCO_2$ - $1xCO_2$.
- The 5 to 95% confidence interval is 3.2 to 4.1 W m^{-2}.
- This corresponds to a 25% uncertainty in forcing.

Range of CO_2 Forcing from Earlier Intercomparisons



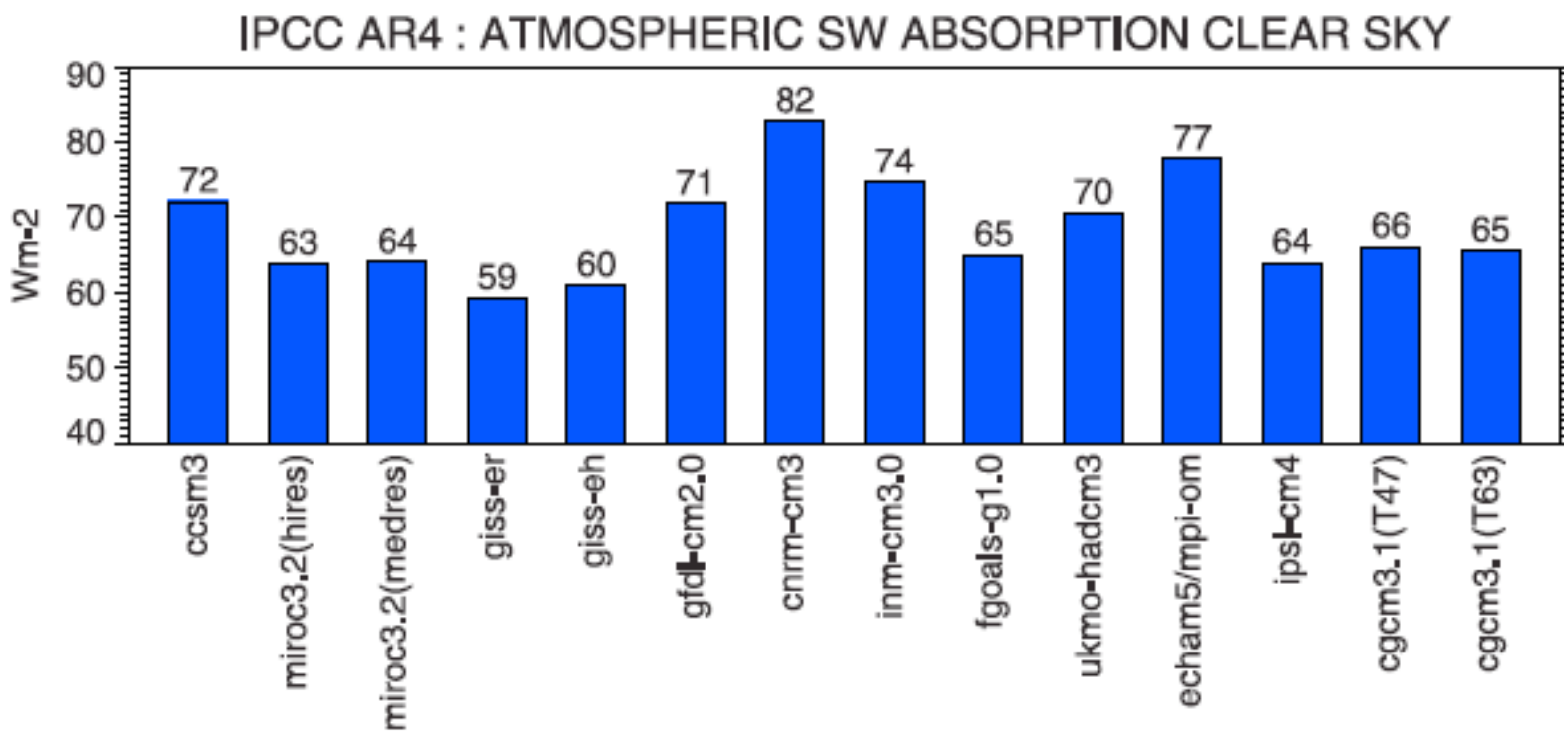
Ellingson et al, 1991



Cess et al, 1993

- GCMs tend to underestimate forcing by CO_2.
- This underestimation is due to omission of bands.
- There is evidence of this omission in current models.

Spread in Atmospheric Shortwave Absorption



Wild et al, 2006

- Average = 69 Wm^{-2}
- Range = 23 Wm^{-2}
- Error = 13 Wm^{-2}

Gas	Absorption
CO_2	1
O_2	2
O_3	14
H_2O	43

Radiation Errors in Climate Models

William D. Collins

National Center for Atmospheric Research

Boulder, Colorado

Errors in Radiation

- Basic radiation fields required for climate modeling:
  - The radiation field itself: $F(x, q, p, t - t_{Jan\ 1})$
  - The trends in the radiation: dF / dt

- The radiation depends upon:

  x = *position*
  q = *composition*
  p = *optics*
  t = *time*

- Errors $e(F)$ in the radiation are:

  $e(F) = (dF / dq)\ e(q) + (dF / dp)\ e(p) + (F - F')$

  where

  $e(q)$ = *Errors in atmospheric composition*
  $e(p)$ = *Errors in optical properties of the constituents*
  $F-F'$ = *Errors in the formulation of radiative transfer*

Topics

- Representation of the Earth's radiative budget
  - Recent improvements in climate models
  - Fidelity of IPCC models to surface data
  - Diversity of modeled shortwave atmospheric absorption
- Representation of radiative forcing of the climate
  - Latest IPCC estimates of historical forcing
  - Diversity of historical and future forcings in IPCC models

Topics

- Representation of the Earth's radiative budget
  - Recent improvements in climate models
  - Fidelity of IPCC models to surface data
  - Diversity of modeled shortwave atmospheric absorption
- Representation of radiative forcing of the climate
  - Latest IPCC estimates of historical forcing
  - Diversity of historical and future forcings in IPCC models
  - Results from the Radiative Transfer Model Intercomparison

Forcing Agents in the IPCC Models

Model	Forcing Agents																	
	Greenhouse Gases						Aerosols										Other	
	CO2	CH4	N2O	Strat O3	Trop O3	CFCs	SO4	Urban	carbon	carbon	Nitrate	Indirect	Indirect	Dust	Volcanic	Sea Salt	Land Use	Solar
BCCR-BCM2.0	1	1	1	C	C	1	2	C						C		C	C	C
BCC-CM1	Y	Y	Y	Y	C	4	4								C		C	C
CCSM3	4	4	4	6	6	4	6		6	6				C	C	C		C
CGCM3.1(T47)	Y	Y	Y	C	C	Y	2							C	C	C	C	C
CGCM3.1(T63)	Y	Y	Y	C	C	Y	2							C	C	C	C	C
CNRM-CM 3	1	1	1	Y	Y	1	2	C						C		C		
CSIRO-Mk3.0	Y	E	E	Y	Y	E	Y											
ECHAM5/MPI-O M	1	1	1	Y	C	1	2					Y						
ECHO-G	1	1	1	C	Y	1	7					Y			C			C
FGOALS-g1.0	4	4	4	C	C	4	4											C
GFDL-CM2.0	Y	Y	Y	Y	Y	Y	Y		Y	Y				C	C	C	C	C
GFDL-CM2.1	Y	Y	Y	Y	Y	Y	Y		Y	Y				C	C	C	C	C
GISS-AO M	5	5	5	C	C	5	2									Y		
GISS-EH	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y		Y	C	Y	C	Y	Y
GISS-ER	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y		Y	C	Y	C	Y	Y
INM-CM3.0	4	4	4	C	C		4								C			C
IPSL-CM4	1	1	1			1	2					Y						
MIROC3.2(H)	Y	Y	Y	Y	Y	Y	Y		Y	Y		Y	Y	Y	C	Y	C	C
MIROC3.2(M)	Y	Y	Y	Y	Y	Y	Y		Y	Y		Y	Y	Y	C	Y	C	C
MRI-CGCM2.3.2	3	3	3	C	C	3	3								C			C
PCM	Y	Y	Y	Y	Y	Y	Y								C			C
UKMO-HadCM3	Y	Y	Y	Y	Y	Y	Y					Y			C			C
UKMO-HadGEM1	Y	Y	Y	Y	Y	Y	Y		Y	Y		Y	Y		C	Y	Y	C
% of Models	100	100	100	96	96	96	100	9	35	35	9	30	22	48	70	57	48	78

Summary of model forcing:

- >96% include major LLGHGs.
- >96% include O_3.
- 100% include SO_4.
- 22% include the 1st indirect effect.

IPCC AR4, 2007

Design of the Intercomparison

- Comparison of instantaneous forcing (not flux):
  - *Stratospheric adjustment is not included.*
  - *Instantaneous forcings are included in WGCM protocol for IPCC simulations.*
- Calculations are for clear-sky conditions.
  - *We use a climatological mid-latitude summer profile.*
  - *Including clouds would complicate the intercomparisons.*
- Radiative effects of constituents:
  - *Absorption by H_2O, O_3, and WMGHGs*
  - *Rayleigh scattering*
  - *Self and foreign line broadening*

Participating AOGCM and LBL groups

AOGCM Groups

Originating group[a]	Country	Model
BCCR	Norway	BCCR-BCM2.0
CCCma	Canada	CGCM3.1(T47/T63)
CCSR/NIES/FRCGC	Japan	MIROC3.2(medres/hires)
CNRM	France	CNRM-CM3
GFDL	USA	GFDL-CM2.0/2.1
GISS	USA	GISS-EH/ER
INM	Russia	INM-CM3.0
IPSL	France	IPSL-CM4
LASG/IAP	China	FGOALS-g1.0
MIUB/METRI/KMA	Germany/Korea	ECHO-G
MPIfM	Germany	ECHAM5/MPI-OM
MRI	Japan	MRI-CGCM2.3.2
NCAR	USA	CCSM3
NCAR	USA	PCM
UKMO	UK	HadCM3
UKMO	UK	HadGEM1

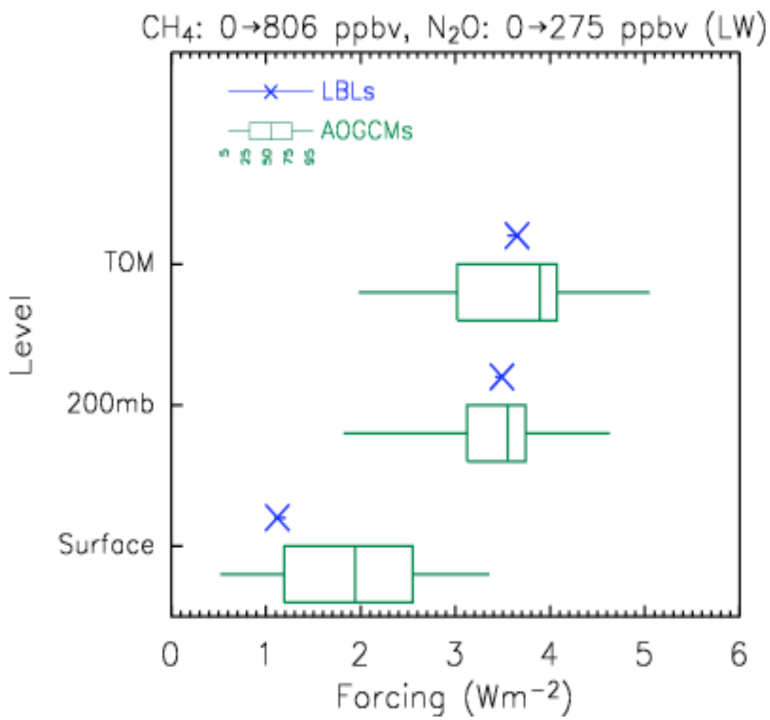
LBL Modelers

Originating group[a]	Country	Model	Reference
GFDL	USA	GFDL LBL	*Schwarzkopf and Fels* [1985]
GISS	USA	LBL3	–
ICSTM	UK	GENLN2	*Edwards* [1992]; *Zhong et al.* [2001]
LaRC	USA	MRTA	*Kratz and Rose* [1999]
UR	UK	RFM	*Dudhia* [1997]; *Stamnes et al.* [1988]

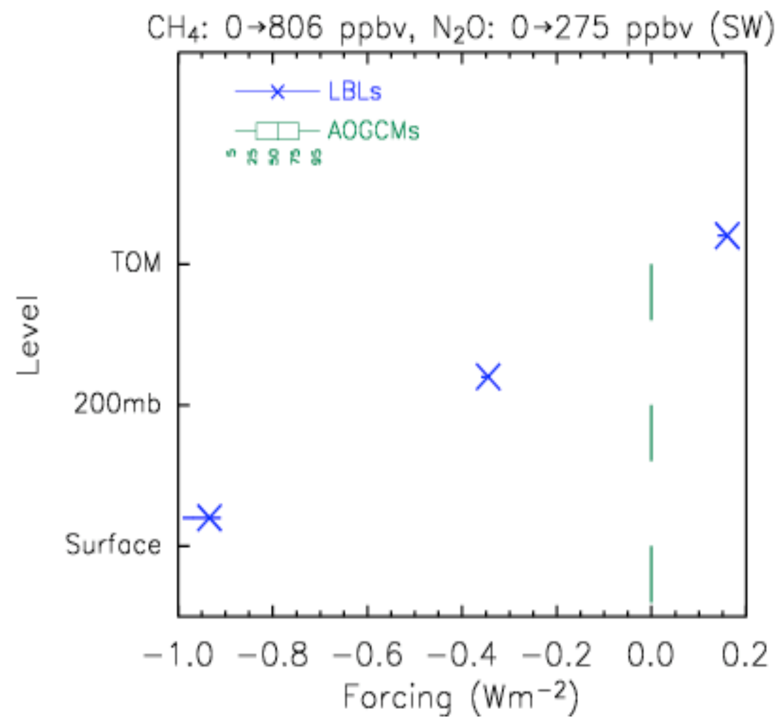
- There are 16 groups submitting simulations from 23 AOGCMs to the IPCC AR4.
- RTMIP includes 14 of these groups and 20 of the AOGCMs.

Forcing by methane and nitrous oxide

Longwave



Shortwave



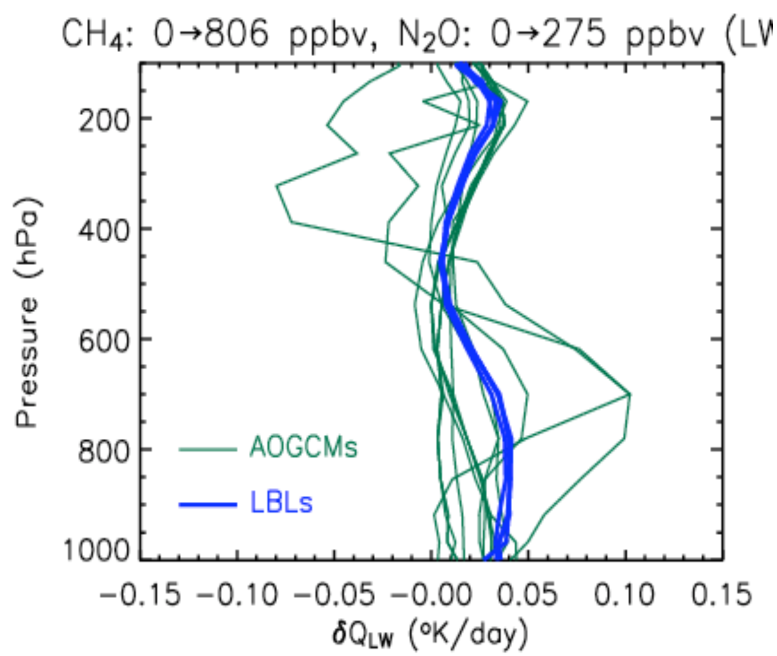
Longwave: The overestimation of surface forcing is statistically significant.
Shortwave: None of the codes treat the effects of CH_4 and N_2O.

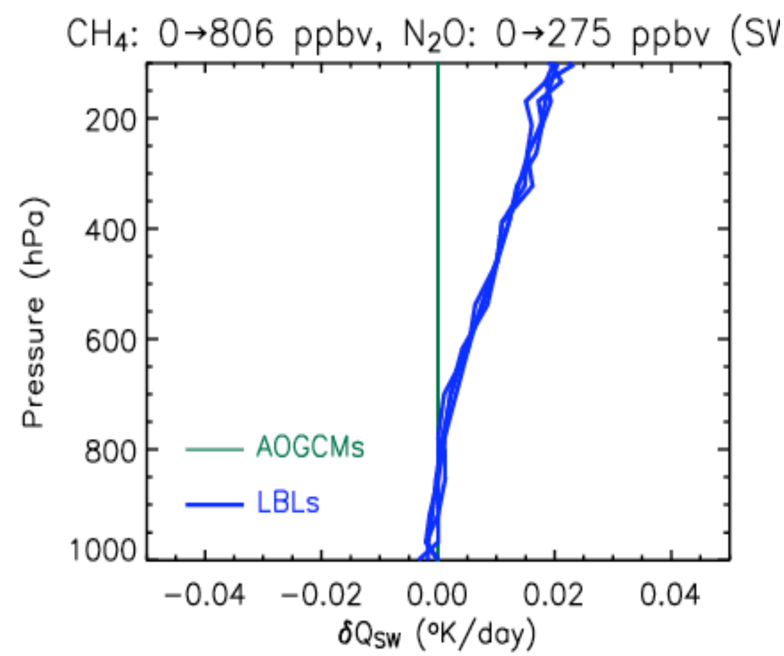
Collins et al, 2006

Change in heating rates by CH_4 and N_2O

Longwave

Shortwave



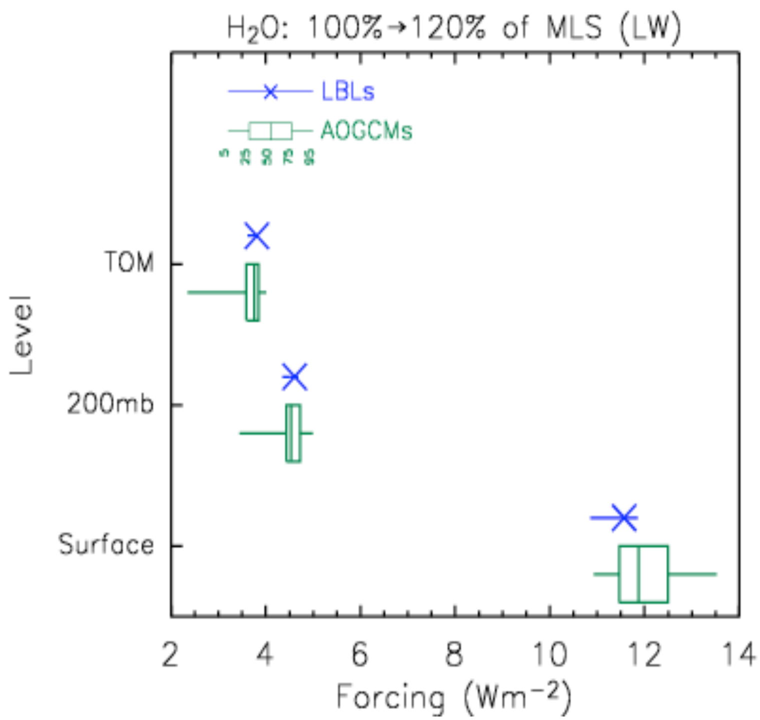


Longwave: Some models have upper tropospheric cooling, an error in sign.
Shortwave: None of the models treat the shortwave heating by CH_4 and N_2O.

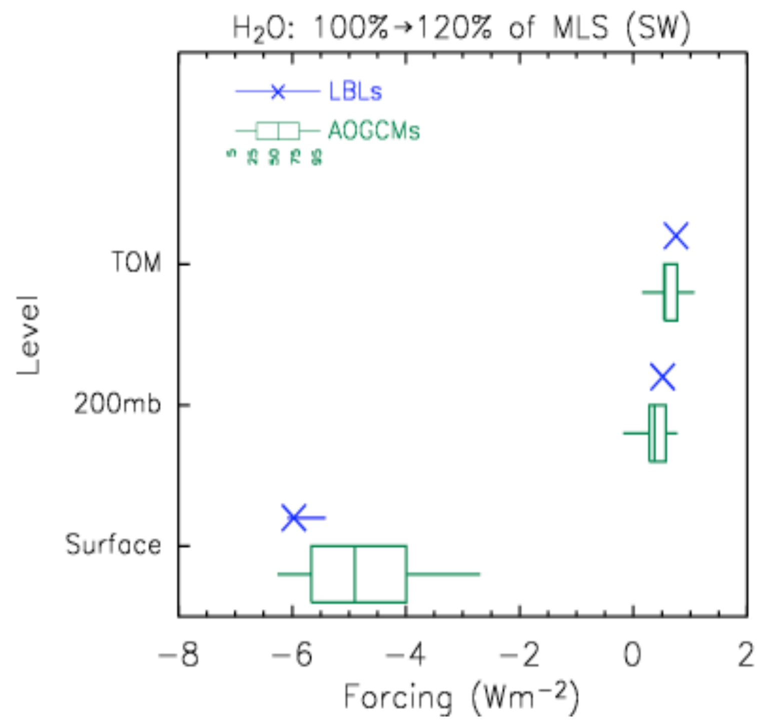
Collins et al, 2006

Forcing by water vapor feedback

Longwave



Shortwave

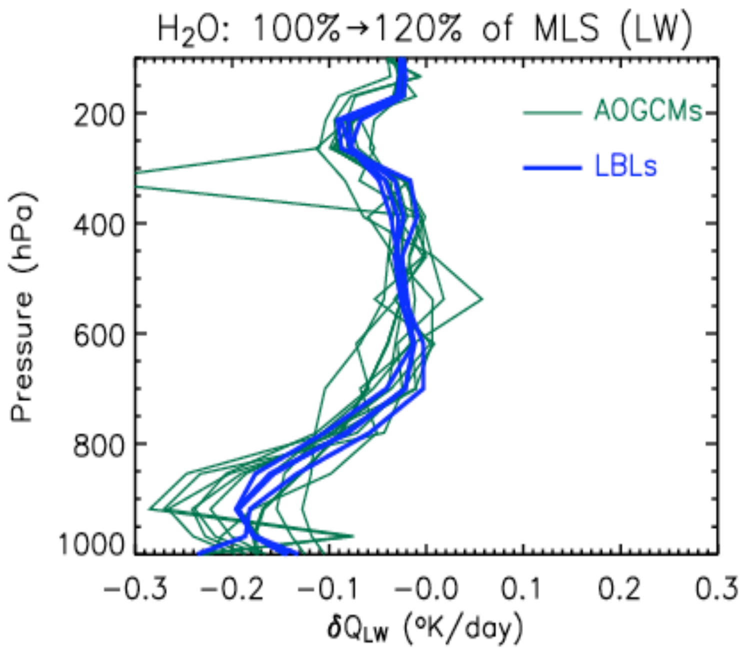


Longwave: None of the differences are statistically significant.
Shortwave: Underestimation of surface forcing magnitude is significant.

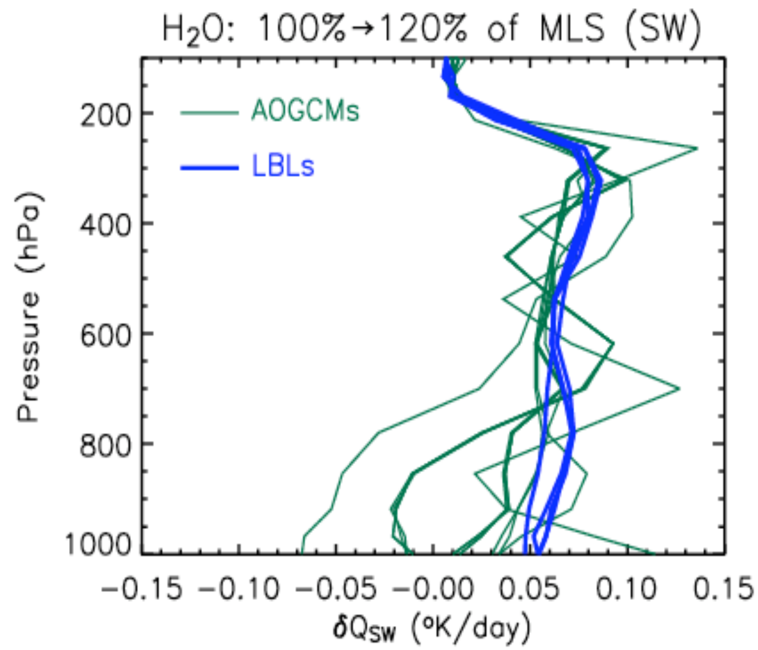
Collins et al, 2006

Change in heating rates by H_2O

Longwave



Shortwave



Longwave: Calculation of cooling by H_2O is generally accurate.
Shortwave:Some models produce tropospheric cooling, an error in sign.

Collins et al, 2006

Conclusions of RTMIP

- No sign errors in the ensemble-mean forcings from AOGCMs!
  - *In 228 forcing calculations, there is only sign error for one model.*

- Forcing by historical changes in WMGHGs:
  - *Mean LW forcings agree to within 0.12 Wm^{-2}.*
  - *Individual LW forcings range from 1.5 to 2.7 Wm^{-2} at TOM.*
  - *This adversely affects separation of forcing from response.*
  - *Mean SW forcings differ by up to 0.37 Wm^{-2} (43% error).*
  - *Large SW errors are related to omission of CH_4 and N_2O.*

- Largest forcing biases occur at the surface level:
  - *Majority of the differences in mean forcings are significant.*
  - *Developers also should insure accuracy of forcing at the surface.*

Acknowledgements

- IPCC AR4 archive: **PCMDI**

- RTMIP coauthors:
  V. Ramaswamy, M.D. Schwarzkopf, Y. Sun, R.W. Portmann,
  Q. Fu, S.E.B. Casanova, J.-L. Dufresne, D.W. Fillmore, P.M.D. Forster,
  V.Y. Galin, L.K. Gohar, W.J. Ingram, D.P. Kratz, M.-P. Lefebvre,
  J. Li, P. Marquet, V. Oinas, Y. Tsushima, T. Uchiyama and W.Y. Zhong

- RTMIP technical support: **DOE ARM program**

- IPCC report:
  Gerald A. Meehl, Thomas F. Stocker, Pierre Friedlingstein, Amadou Gaye, Jonathan Gregory, Akio Kitoh, Reto Knutti, James Murphy, Akira Noda, Sarah Raper, Ian Watterson, Andrew Weaver, and Zong-Ci Zhao

- New methods in radiative transfer: **Andrew Conley**

- Support: **DOE SciDAC program and NSF**

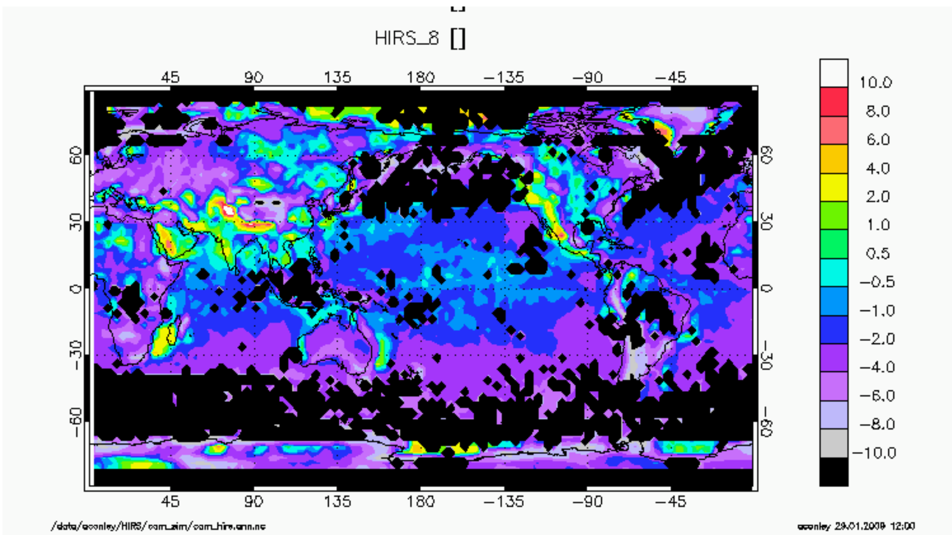
Physics Tests of RRTMG

- RRTMG surface and TOA fluxes differ by < 1% from observations when using *in situ* observations of atmospheric and surface states.
- Bias is much smaller than that between CAM and CERES.
- These results imply that RRTMG fluxes are accurate when the atmospheric and surface states are accurate.
- Thus RRTMG is probably not the cause for the CAM bias.

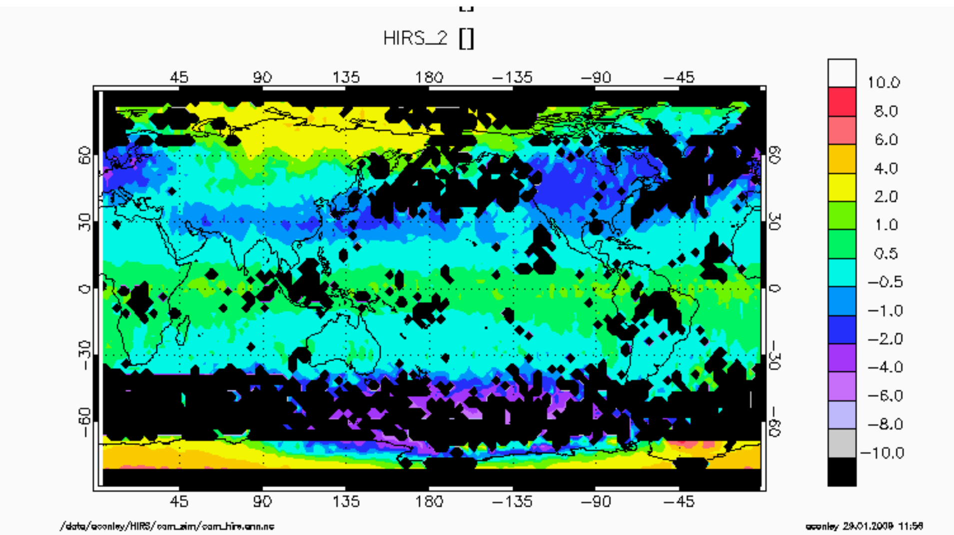
Note: For Circ case 1, RRTMG reproduces LBL LW fluxes to better than 0.1% at TOA and surface.

HIRS analysis of source of OLR bias

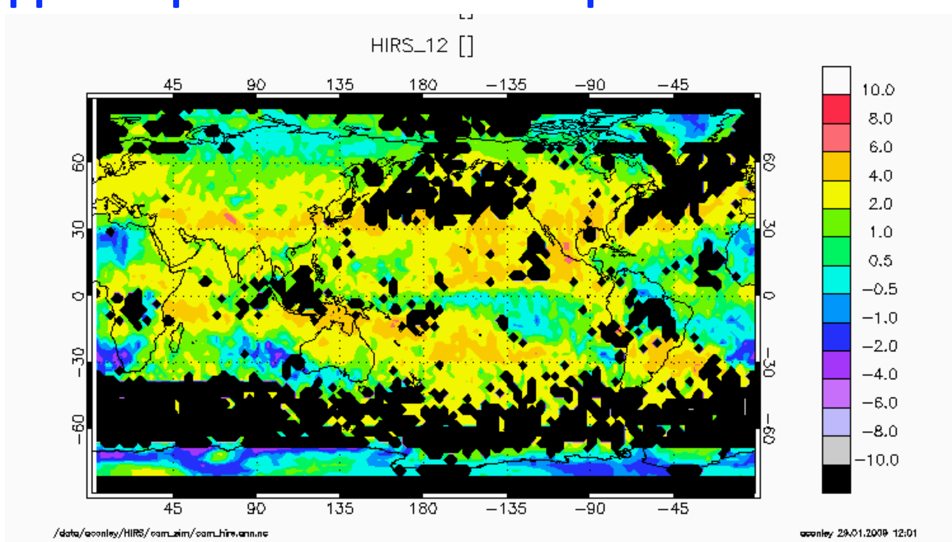
Surface temperature: HIRS-CAM



Upper trop. temperature: HIRS-CAM



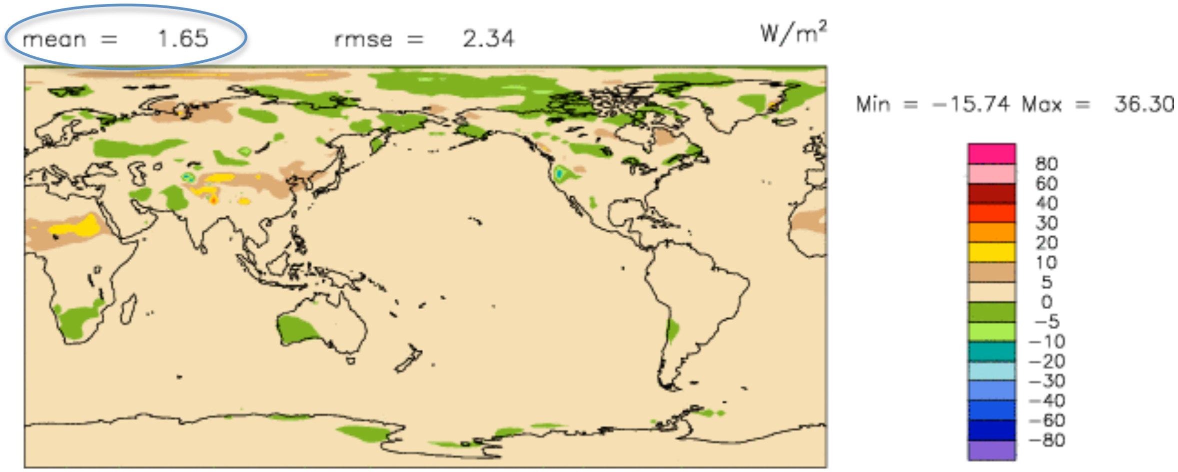
Upper trop. H2O emission temperature: HIRS-CAM



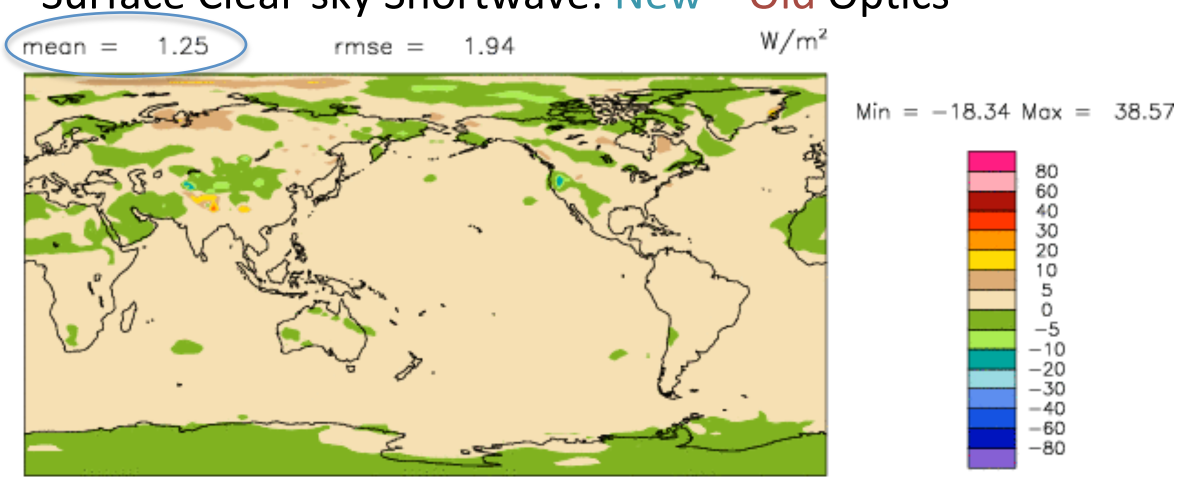
In channels sensitive to upper trop. H2O, CAM underestimates the brightness temp. by 2-4K – too moist?

New aerosol optics

TOA Clear-sky Shortwave: New – Old Optics

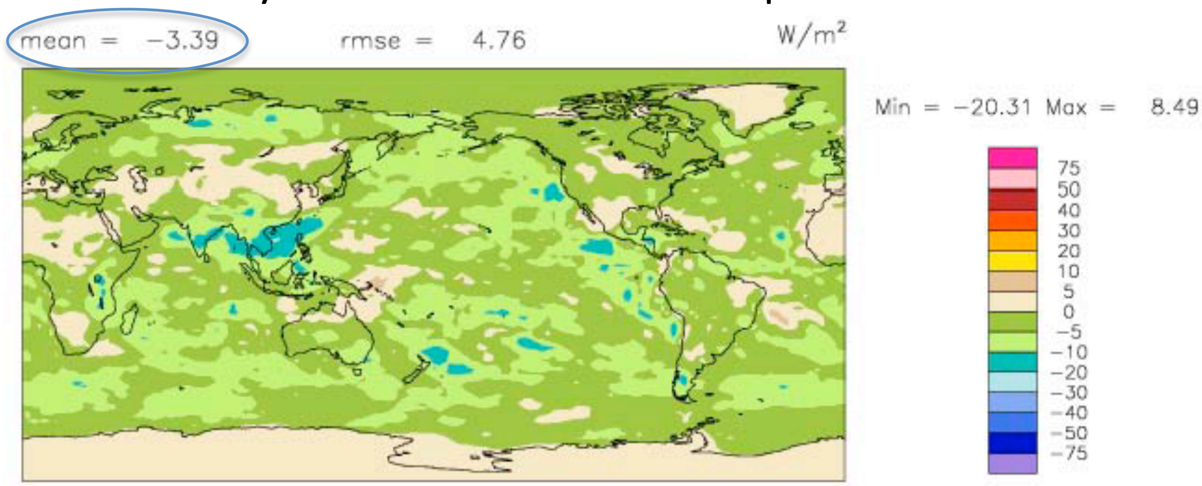


Surface Clear-sky Shortwave: New – Old Optics

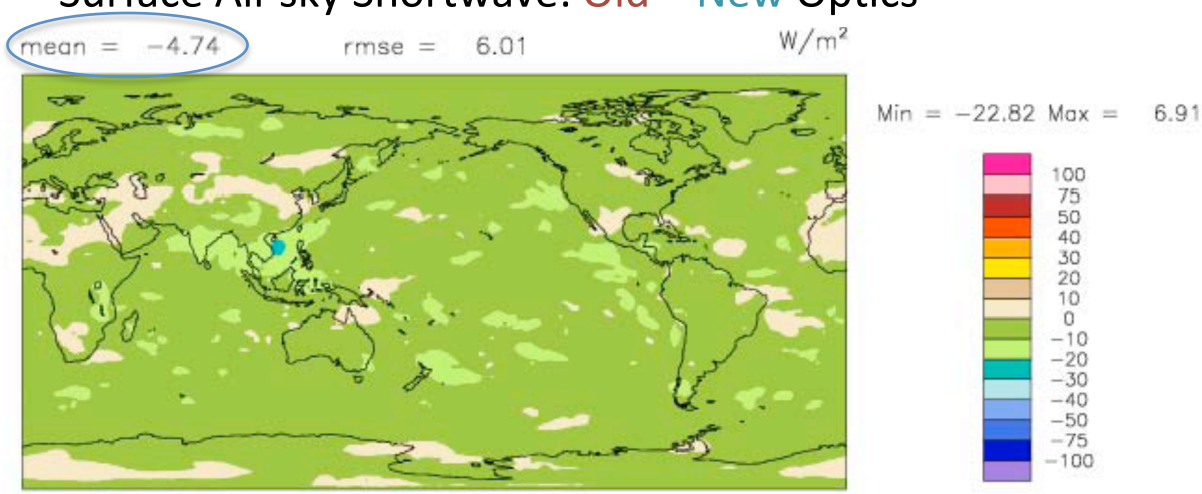


New cloud optics

TOA All-sky Shortwave: Old – New Optics



Surface All-sky Shortwave: Old – New Optics



Both aerosol and cloud optics lower planetary albedo.

Topics

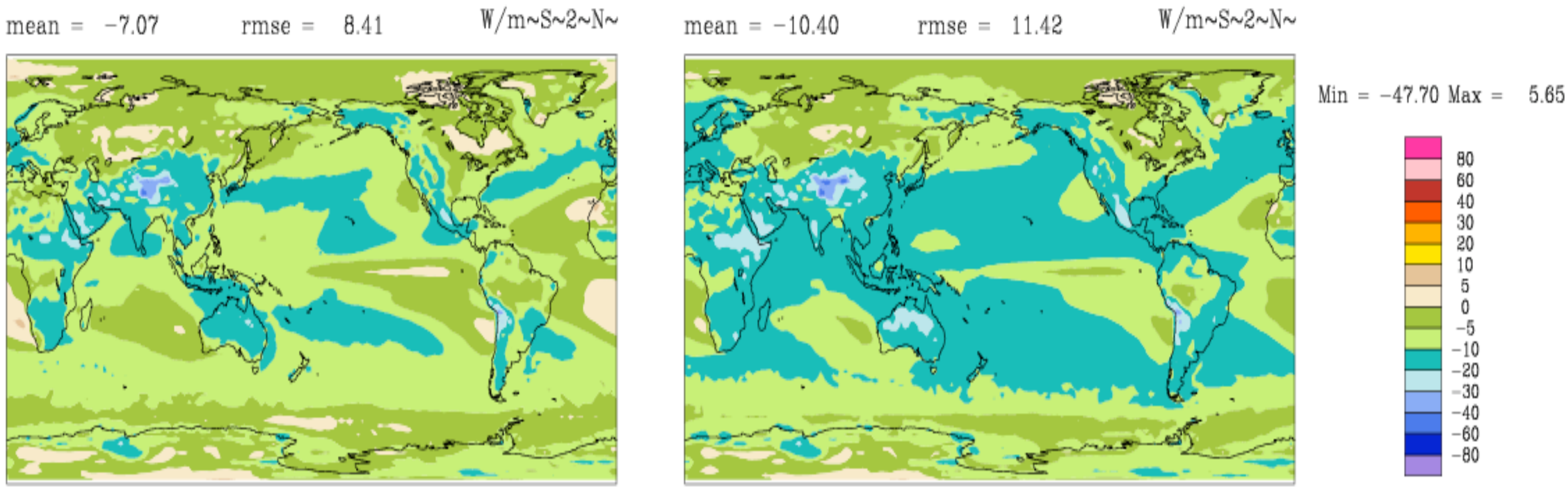
- Representation of the Earth's radiative budget
  - Recent improvements in climate models
  - Fidelity of IPCC models to surface data
  - Diversity of modeled shortwave atmospheric absorption

- Representation of radiative forcing of the climate
  - Latest IPCC estimates of historical forcing
  - Diversity of historical and future forcings in IPCC models
  - Results from the Radiative Transfer Model Intercomparison

Issue: Bias in clear-sky OLR

CAMRT – CERES2
-7.07 W/m^2

RRTMG – CERES2
-10.40 W/m^2



Hypotheses for origin of OLR bias

- Physics of RRTMG
- Integration of RRTMG with CAM
- Surface Boundary Condition
- Composition of Atmosphere