Radiation Errors in Climate Models

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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*
  $F\text{-}F'$ = *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
  - Results from the Radiative Transfer Model Intercomparison

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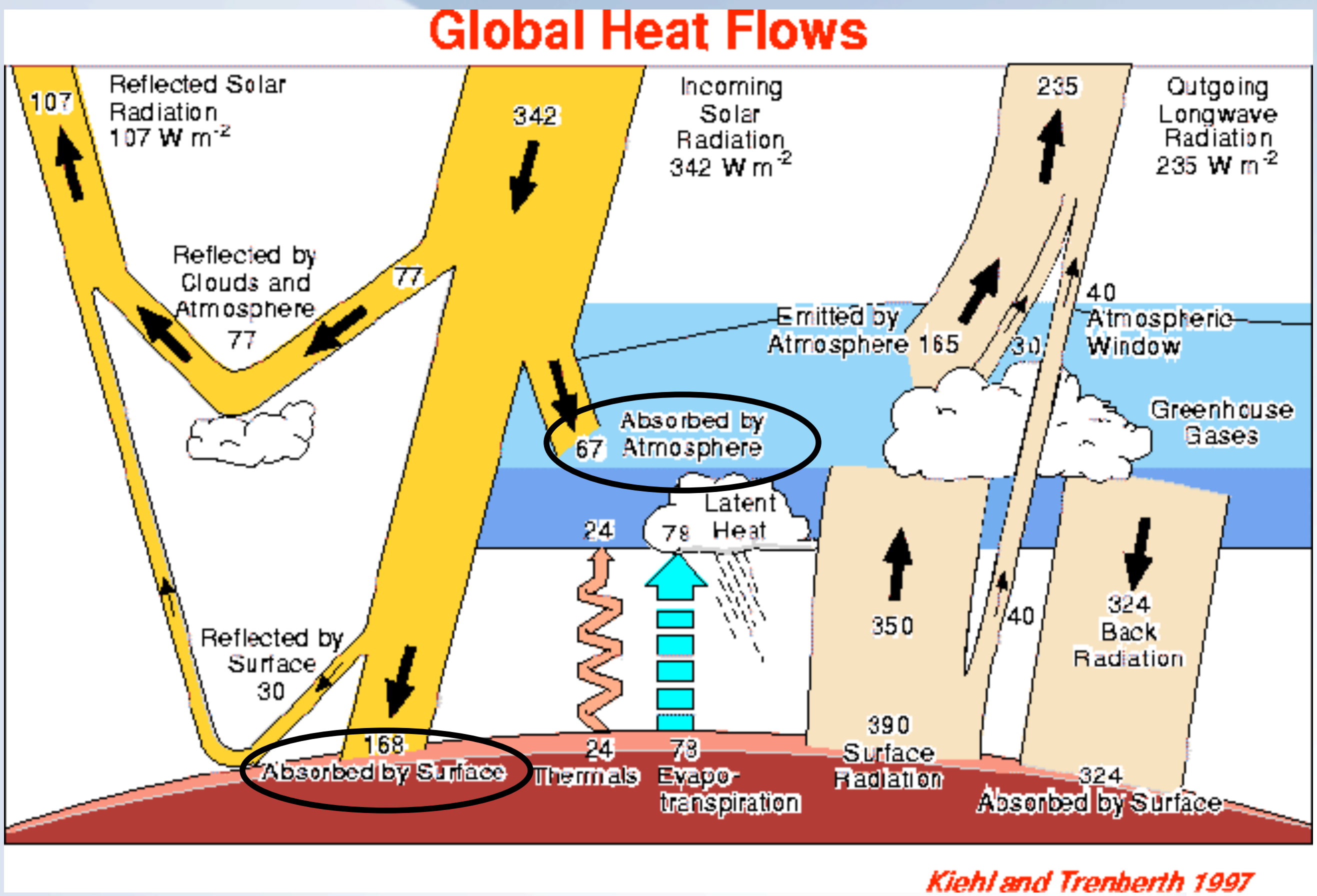
The Earth's Radiative Budget



- Improvements in modeling surface insolation
- Range of modeled atmospheric solar absorption

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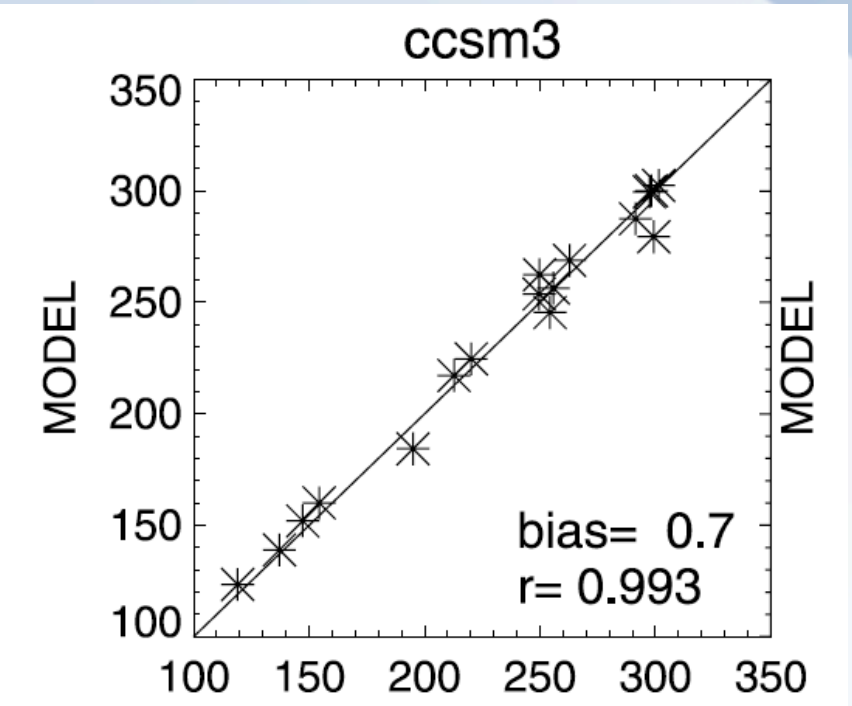
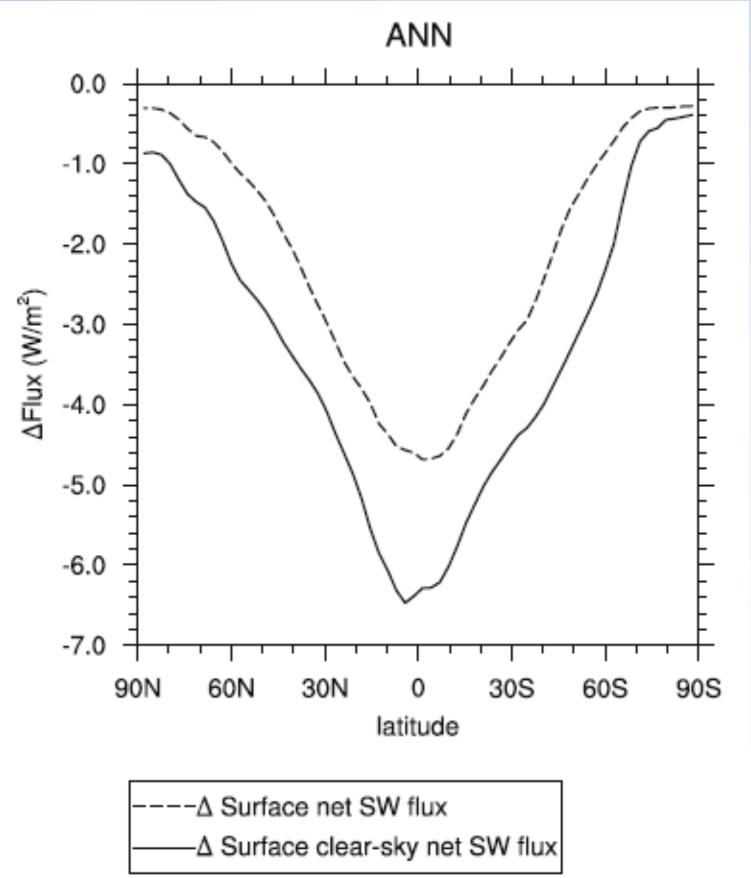
Improved Surface Shortwave Fluxes

Model vs. Surface Radiometers



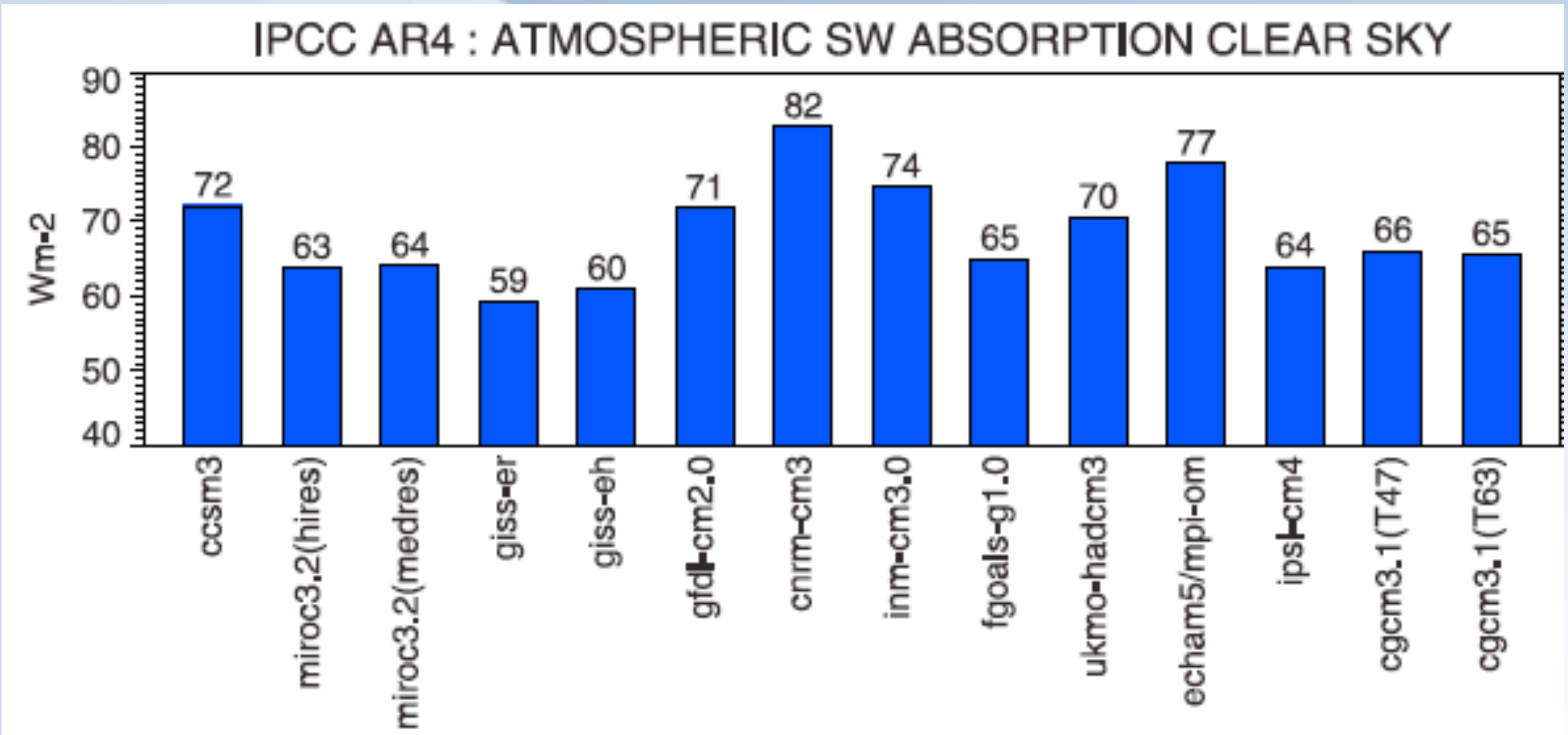
Wild et al, 2006

Effect of Updating H2O Spectroscopy



Collins et al, 2006

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

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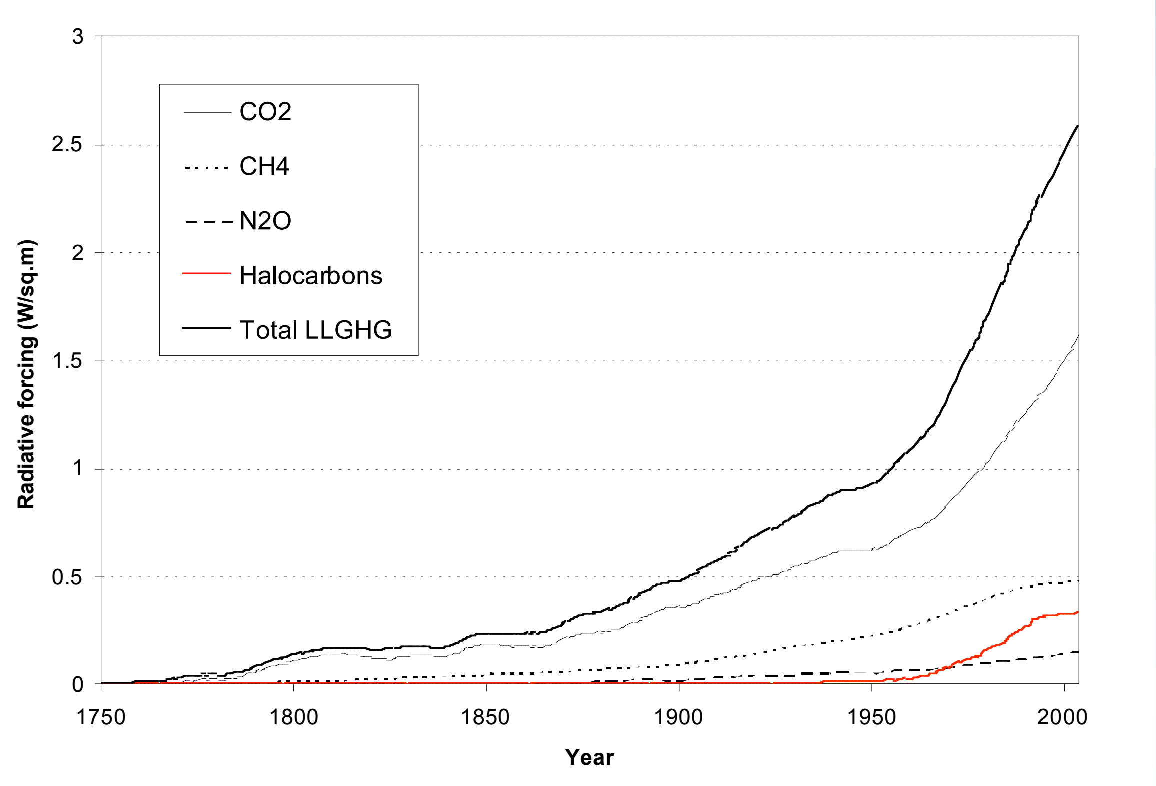
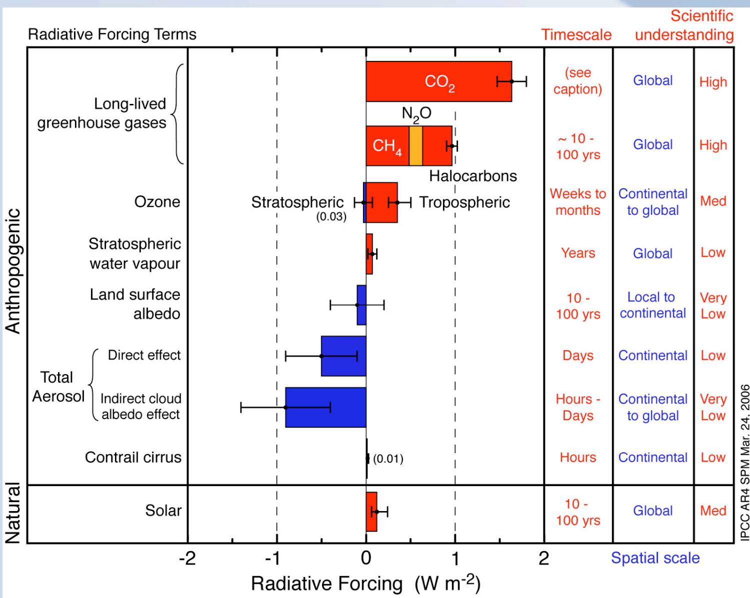
Concept of Radiative Forcing

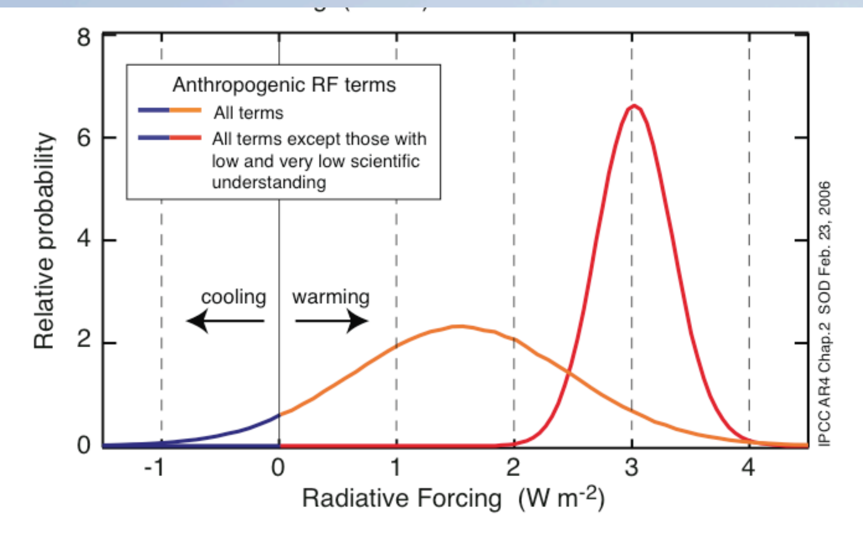


IPCC AR4, 2007

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

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}

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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-CM3	1	1	1	Y	Y	1	2	C						C		C		
CSIRO-Mk3.0	Y	E	E	Y	Y	E	Y											
ECHAM5/MPI-OM	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-AOM	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

IPCC AR4, 2007

Summary of model forcing:

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

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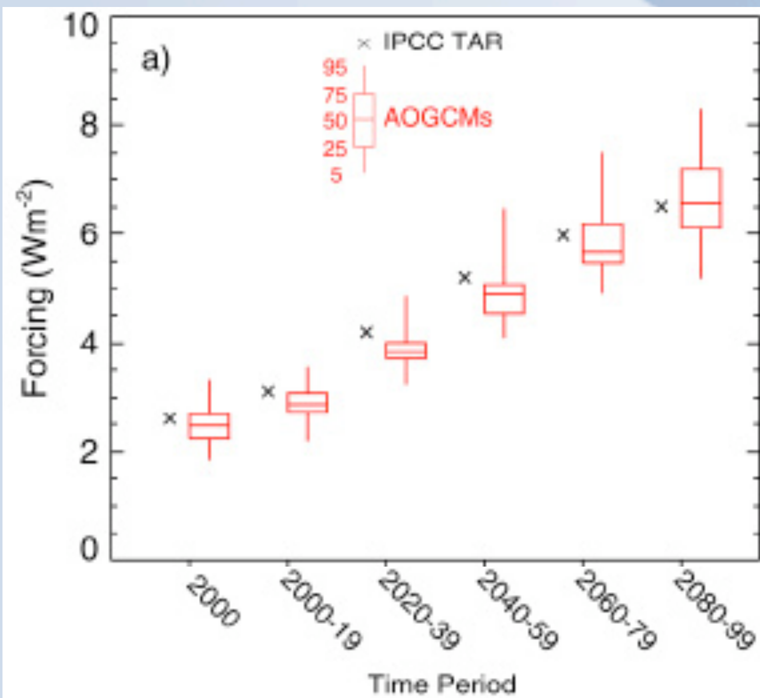
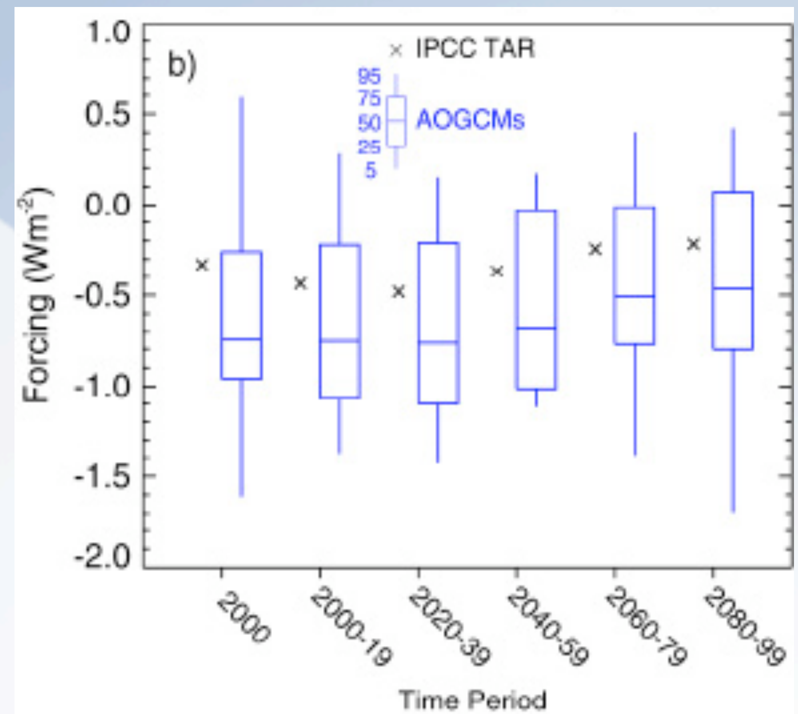
Radiative Forcing for the A1B SRES Scenario: 20 AOGCMs



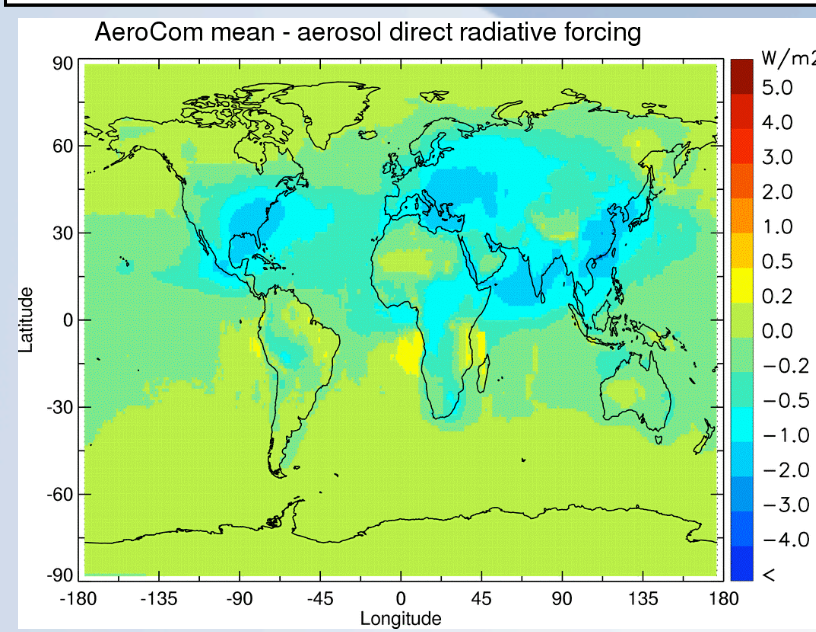


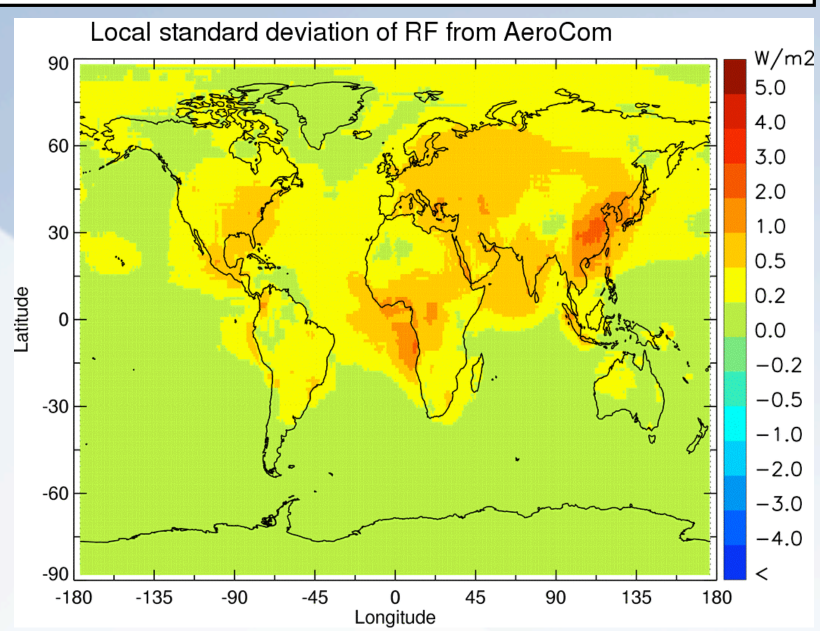
IPCC AR4, 2007

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}.

Model Estimates of Aerosol Radiative Forcing

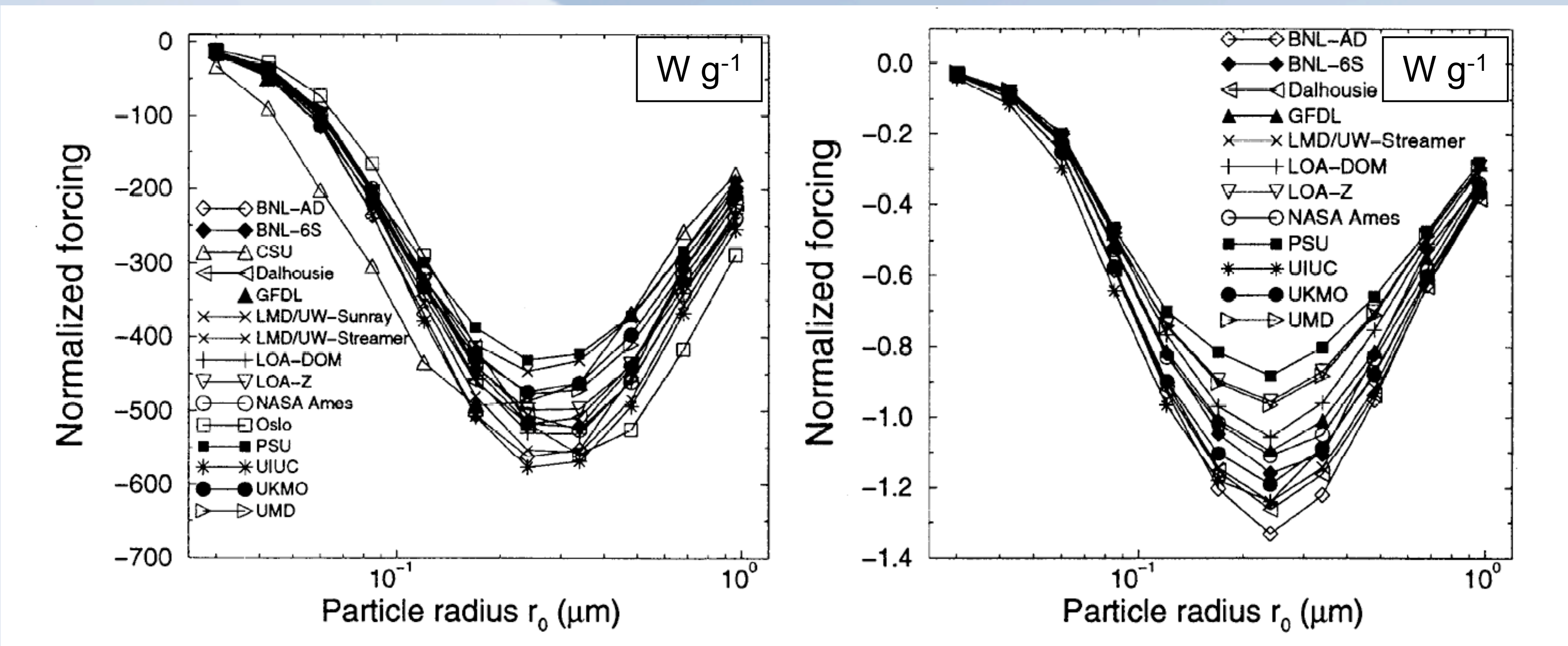




IPCC AR4, 2007

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

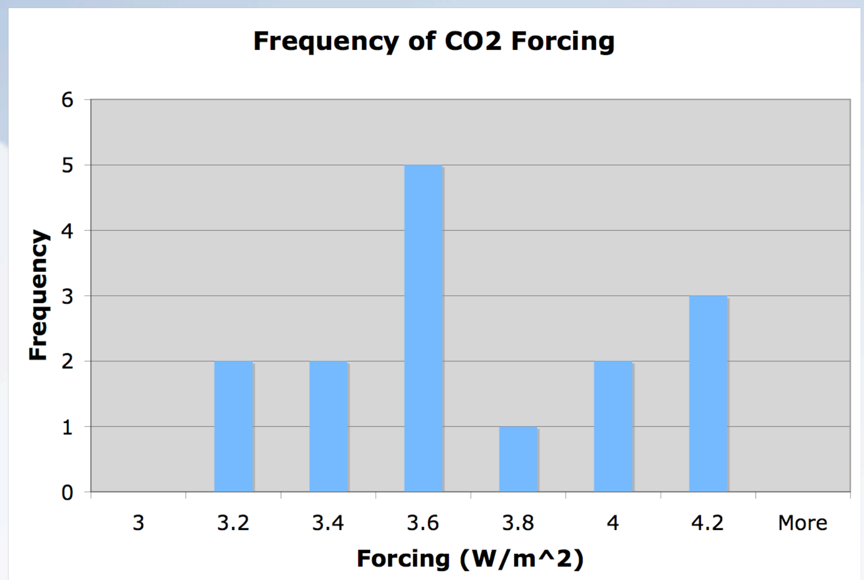


Boucher et al, 1998

- 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

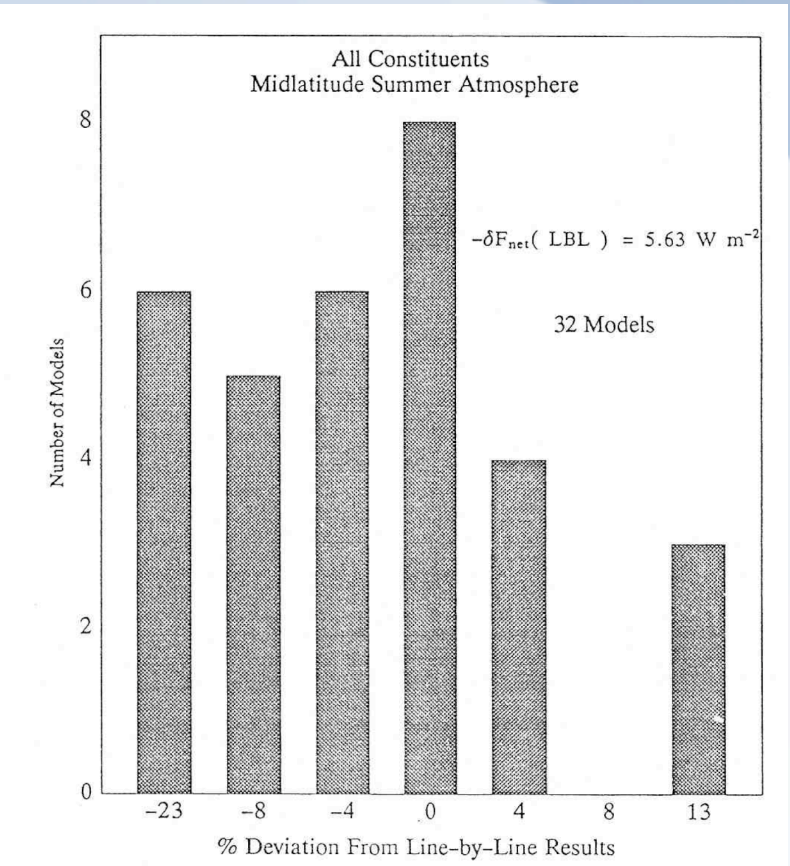
Group	Model	Total (W m^{-2})
CCCma	CGCM 3.1 (T47/T63)	3.32
CSIRO	CSIRO-Mk3.0	3.47
GISS	GISS-EH/ER	4.06
GFDL	GFDL-CM2.0/2.1	3.50
IPSL	IPSL-CM4	3.48
CCSR/NIES/FRCGC	MIROC 3.2-hires	3.14
CCSR/NIES/FRCGC	MIROC 3.2-medres	3.09
MPI	ECHAM5/MPI-OM	4.01
MRI	MRI-CGCM2.3.2	3.47
NCAR/CRIEPI	CCSM3	3.95
UKMO	UKMO-HadCM3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



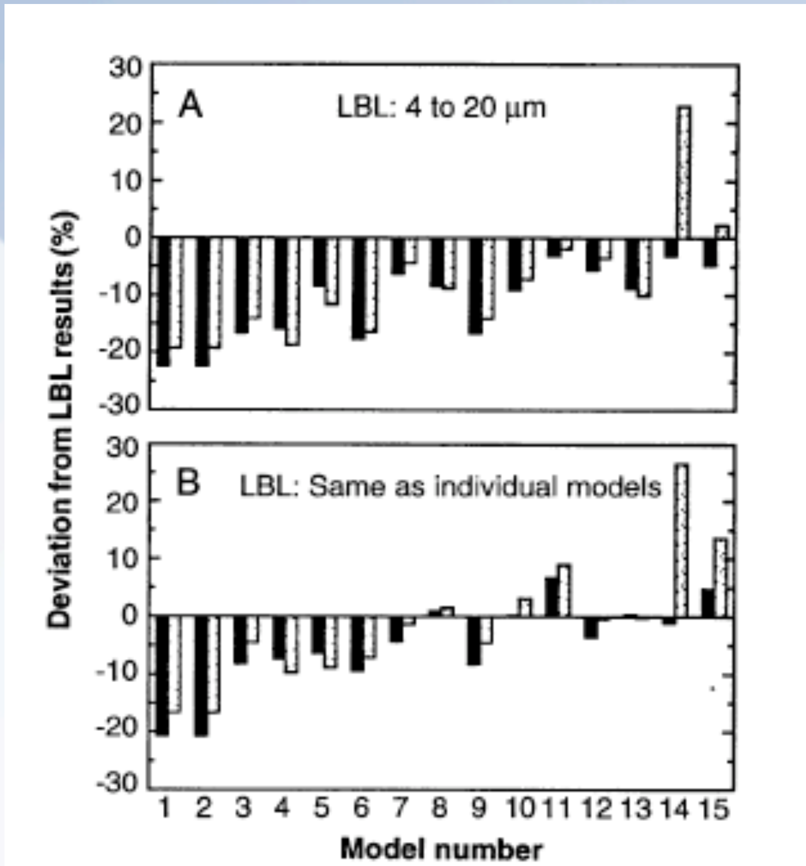
IPCC AR4, 2007

- 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.

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Radiative Forcing and Climate Sensitivity

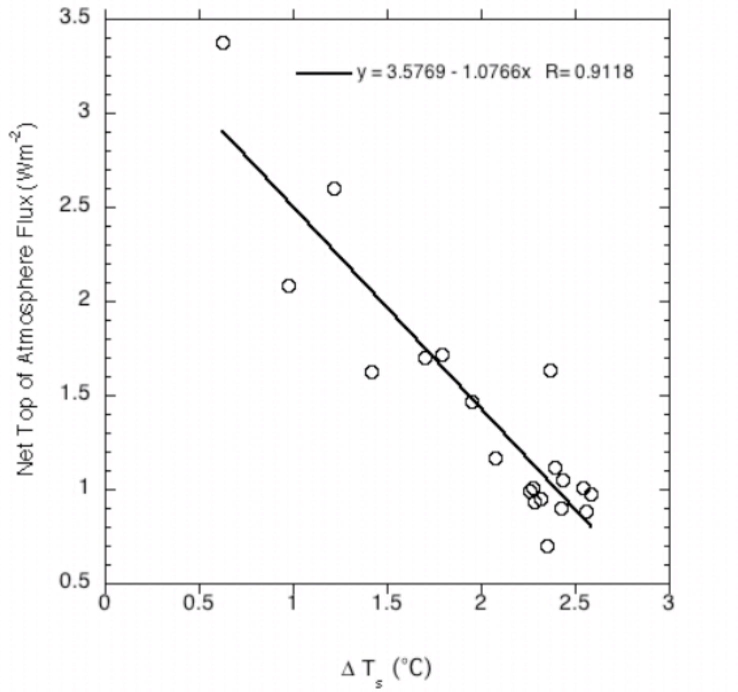

Figure 1. Change in net forcing (Wm^{-2}) at the model top versus change in surface temperature (°C) from the T42 CAM3 slab ocean model simulation for doubled CO_2. Each data point is the annual mean value from the first 20 years of the simulation.

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?

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Link between Changing Rainfall and Temperature

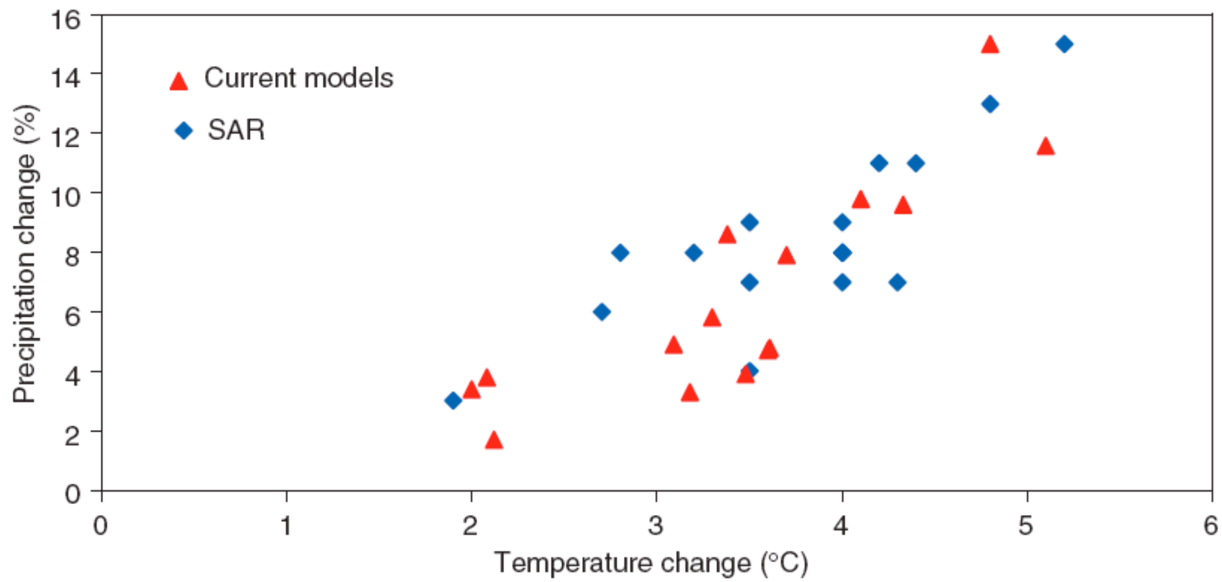

Figure 9.18: Equilibrium climate and hydrological senstitivies from AGCMs coupled to mixed-layer ocean components; blue diamonds from the SAR, red triangles from models in current use (LeTreut and McAvaney, 2000 and Table 9.1).

IPCC TAR, 2001

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

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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*
  - *$2\times CO_2 - 1\times CO_2$ and $4\times CO_2 - 1\times CO_2$*
  - *Combinations of increased CH_4, N_2O, and CFCs*
  - *Feedbacks from increased H_2O*

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

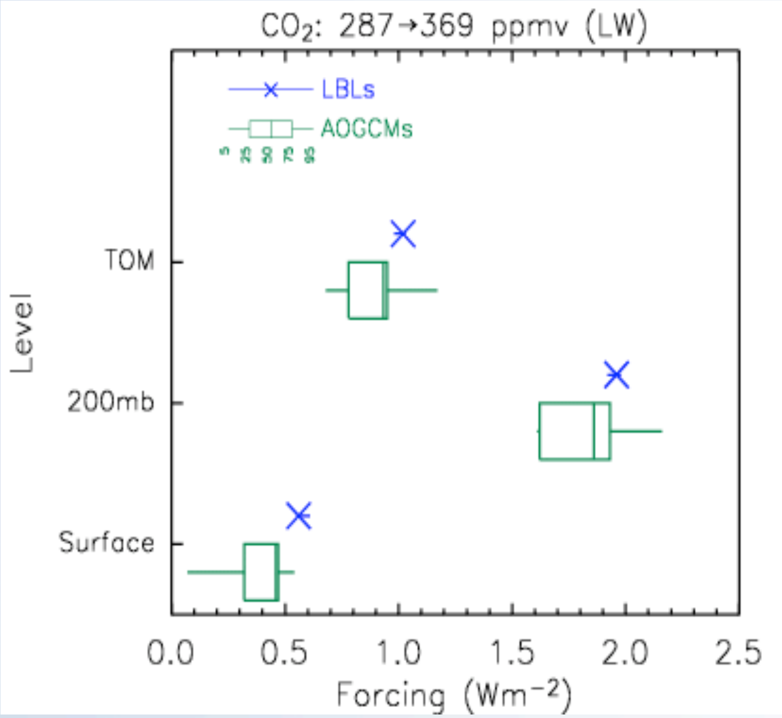
Originating group[a]	Country	Model	Reference
GFDL	USA	GFDL LBL	*Schwarzkopf and Fels* [1985]
GISS	USA	LBL3	–
ICSTM	UK	GENLN2	*Edwards* [1992]; *Zhong et al.* [2001]
LaRC	USA	MRTA	*Kratz and Rose* [1999]
UR	UK	RFM	*Dudhia* [1997]; *Stamnes et al.* [1988]

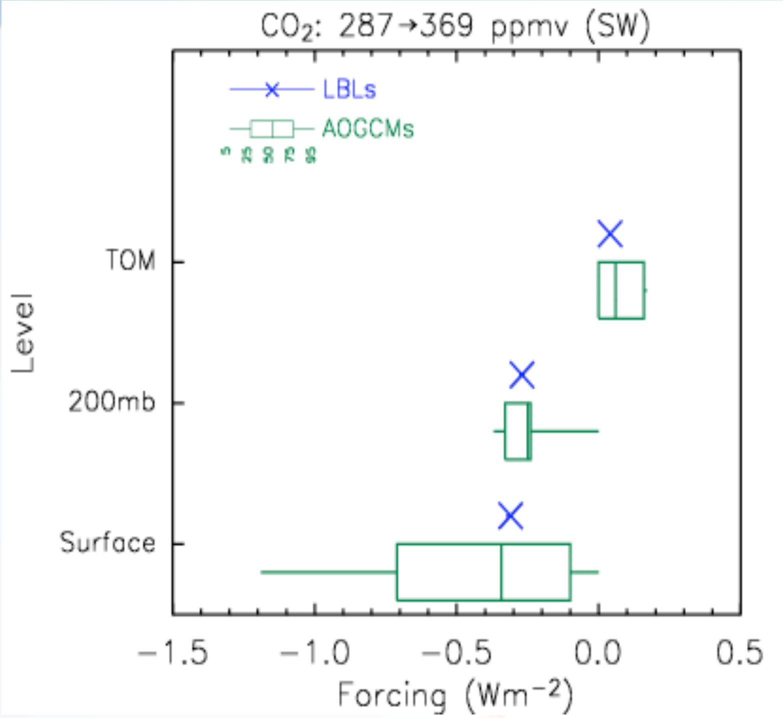
- There are 16 groups submitting simulations from 23 AOGCMs to the IPCC AR4.
- RTMIP includes 14 of these groups and 20 of the AOGCMs.

Forcing by historical increase in CO_2

Longwave

Shortwave





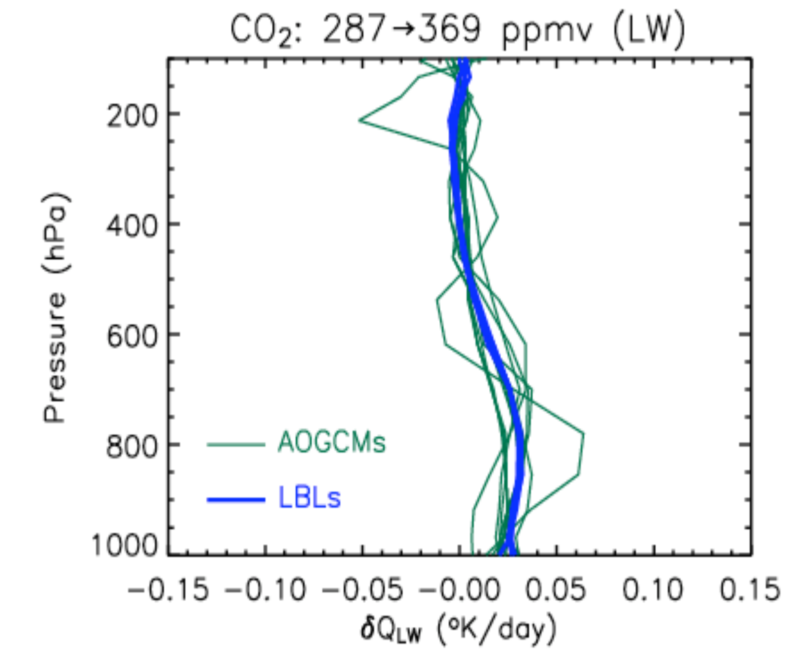
Longwave: Relative difference is 8% at 200hPa and 33% at surface.
Shortwave: Large range in surface forcing: RMS / mean = 0.94

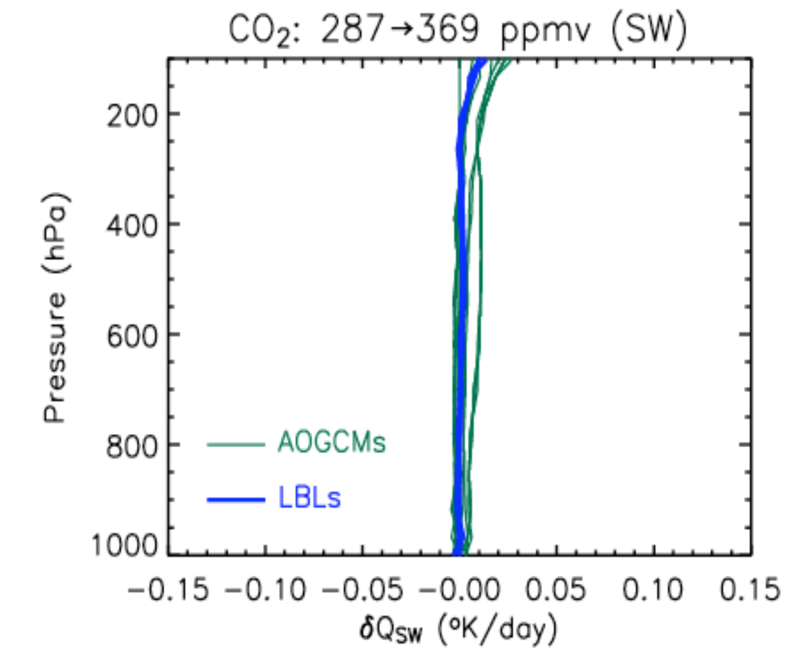
Collins et al, 2006

Change in heating rates by CO_2

Longwave

Shortwave



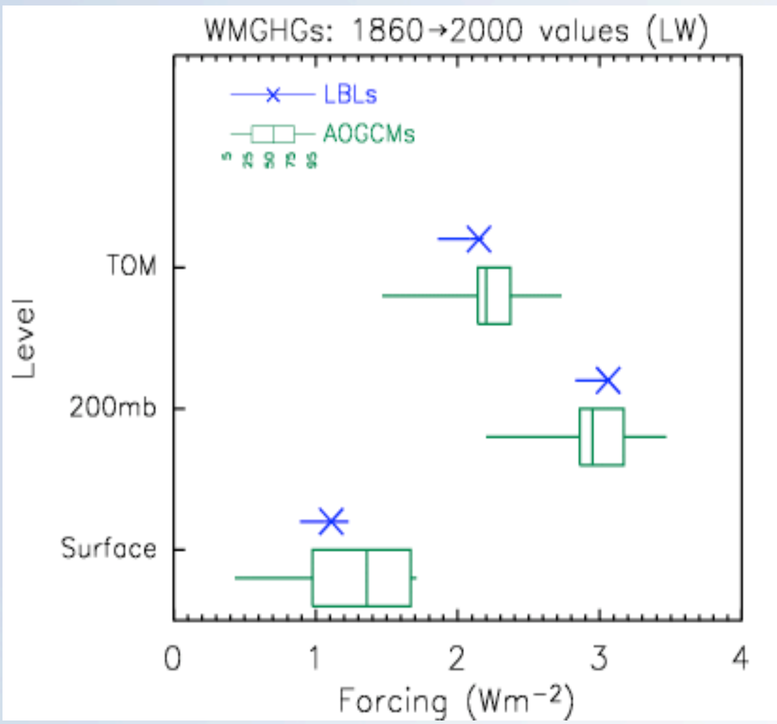


Longwave: Most models agree in magnitude and sign of the additional heating.
Shortwave: Average model agrees in magnitude and sign of the additional heating.

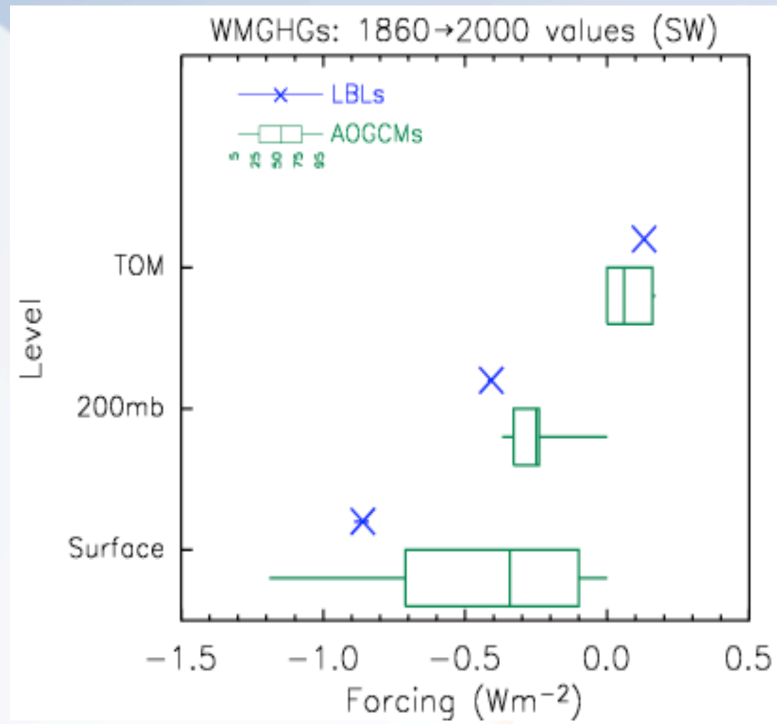
Collins et al, 2006

Forcing by historical increase in GHGs

Longwave



Shortwave



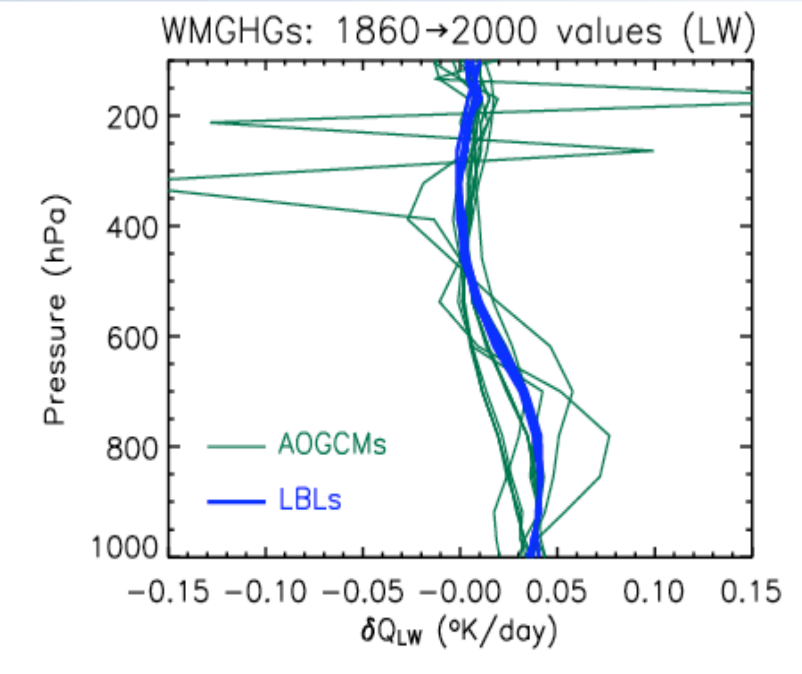
Longwave: None of the differences are statistically significant.
Shortwave:All of the differences are statistically significant.

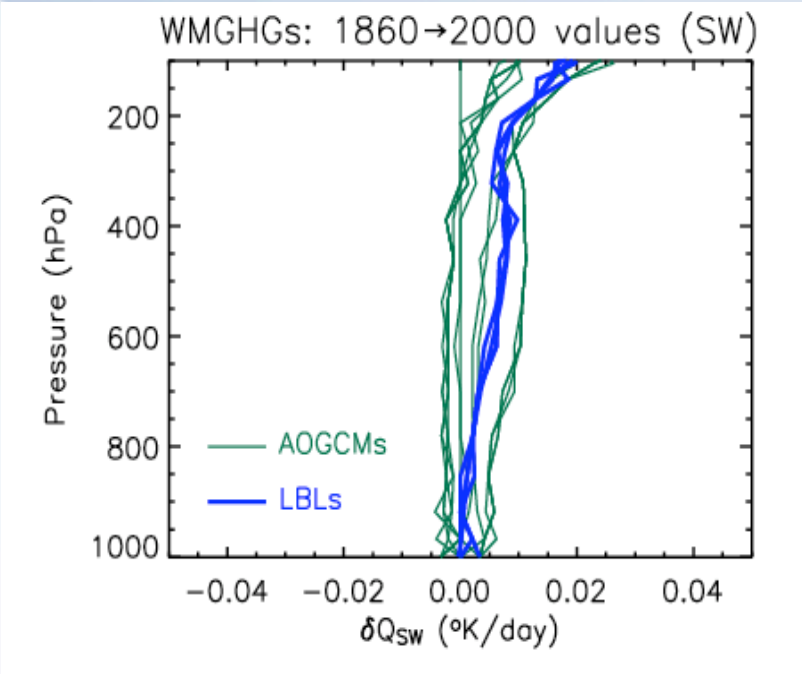
Collins et al, 2006

Change in heating rates by WMGHGs

Longwave

Shortwave



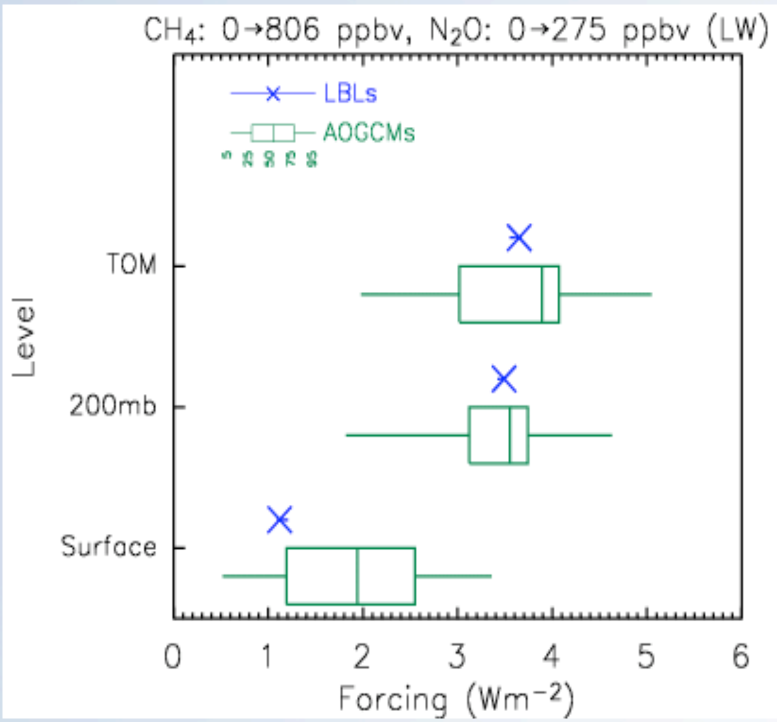


Longwave: Some models show evidence of numerical artifacts.
Shortwave:Some models produce tropospheric cooling, an error in sign.

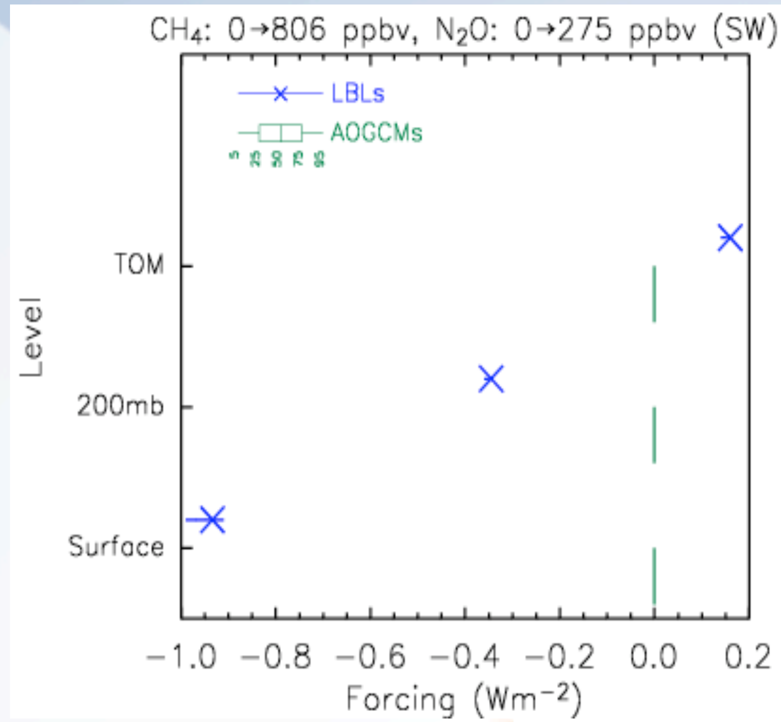
Collins et al, 2006

Forcing by methane and nitrous oxide

Longwave



Shortwave



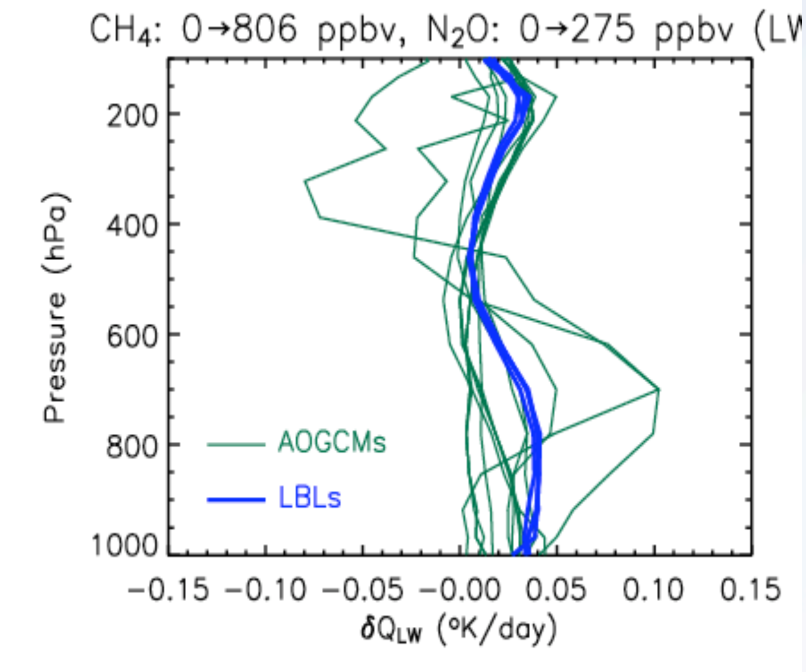
Longwave: The overestimation of surface forcing is statistically significant.
Shortwave: None of the codes treat the effects of CH_4 and N_2O.

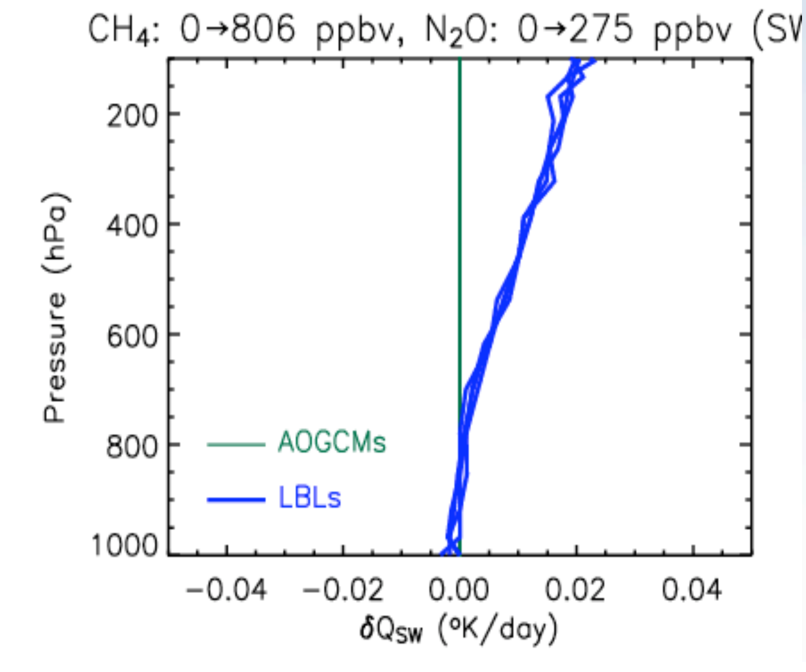
Collins et al, 2006

Change in heating rates by CH_4 and N_2O

Longwave

Shortwave



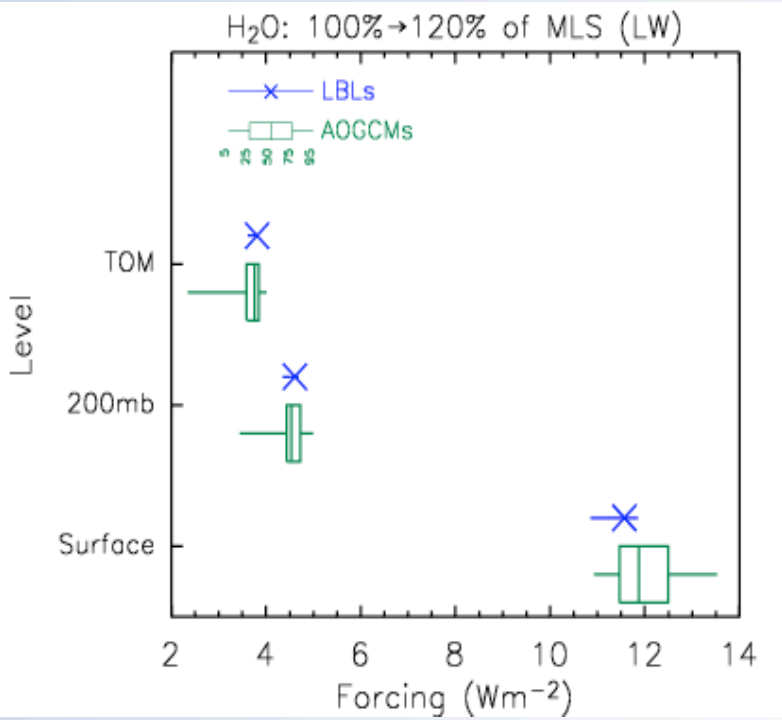


Longwave: Some models have upper tropospheric cooling, an error in sign.
Shortwave: None of the models treat the shortwave heating by CH_4 and N_2O.

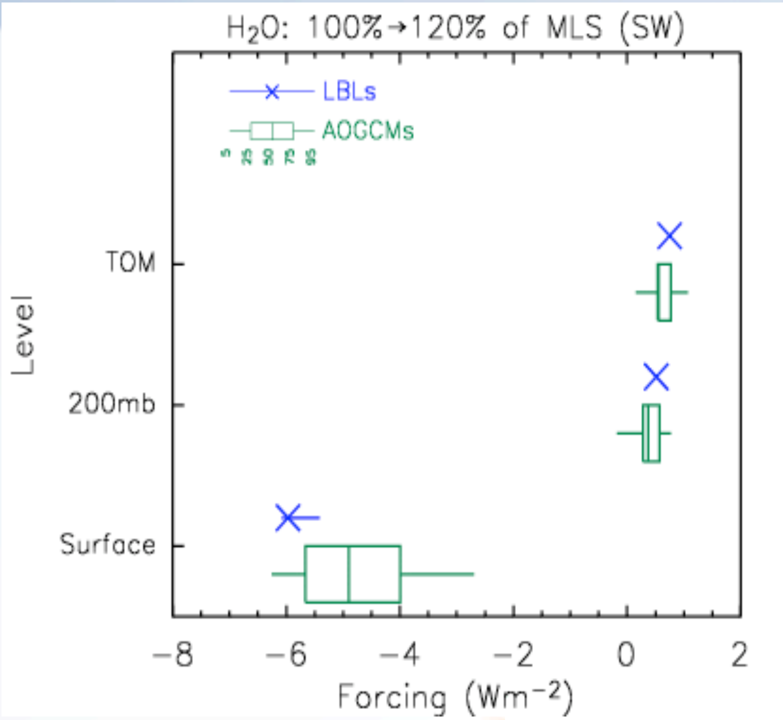
Collins et al, 2006

Forcing by water vapor feedback

Longwave



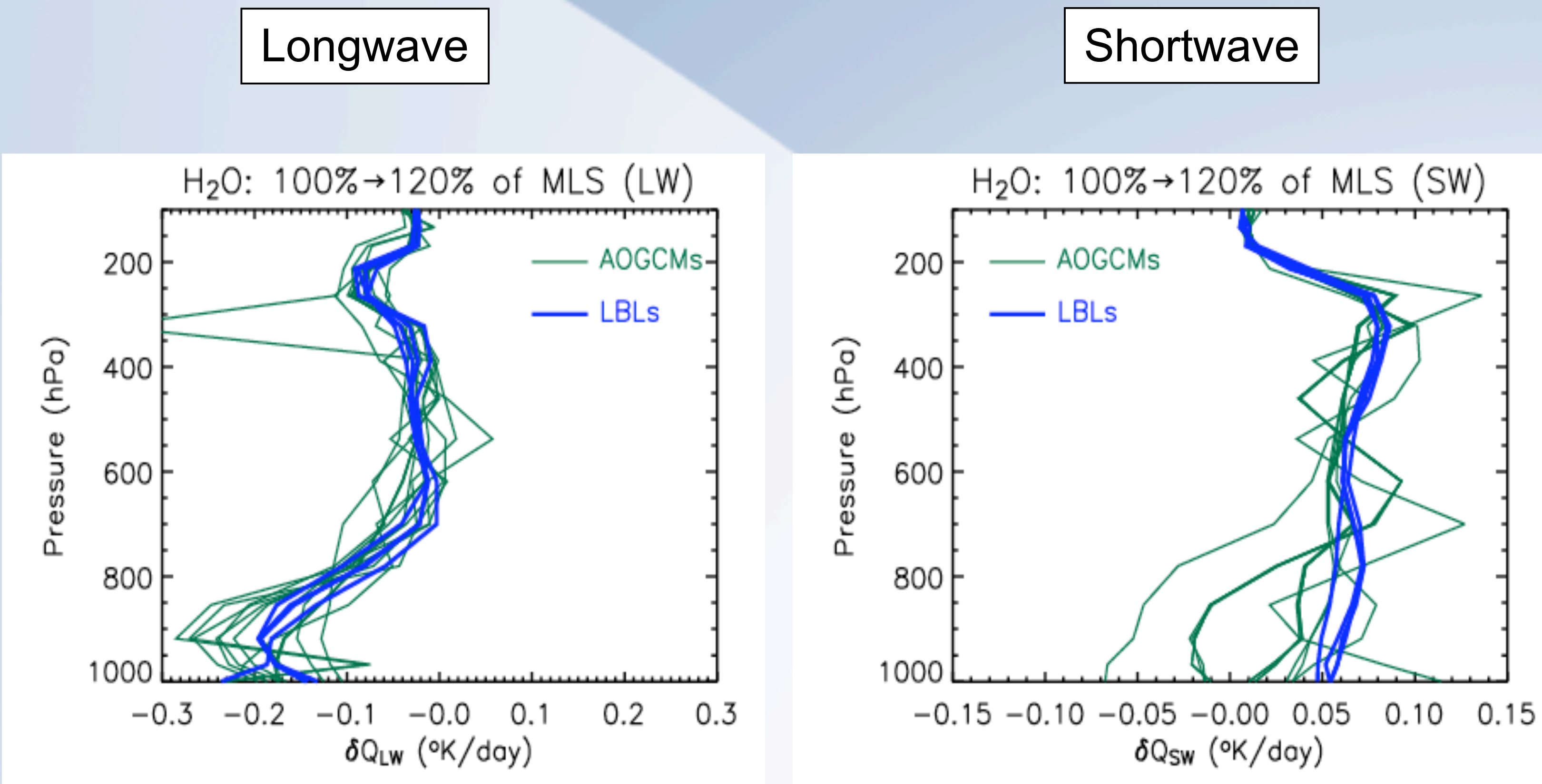
Shortwave



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: 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:
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