Atmospheric radiative controls on global precipitation

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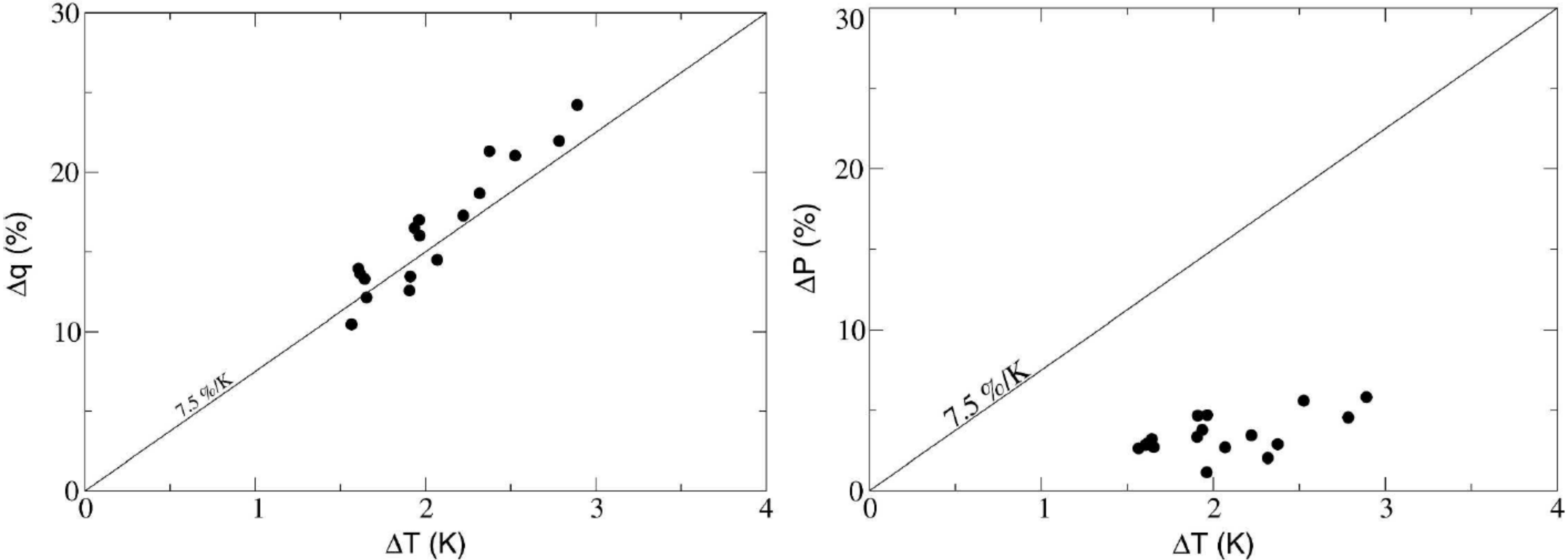
Outline

- Background on precipitation in the atmospheric energy budget

- Part 1: Atmospheric radiative cooling response to CO_2 increase

- Part 2: Black carbon forcing and global-mean precipitation inter-model spread in A1b scenario of AR4

Precipitation increases more slowly than water vapor with global warming: Why?



Moisture increases at **7%/K**

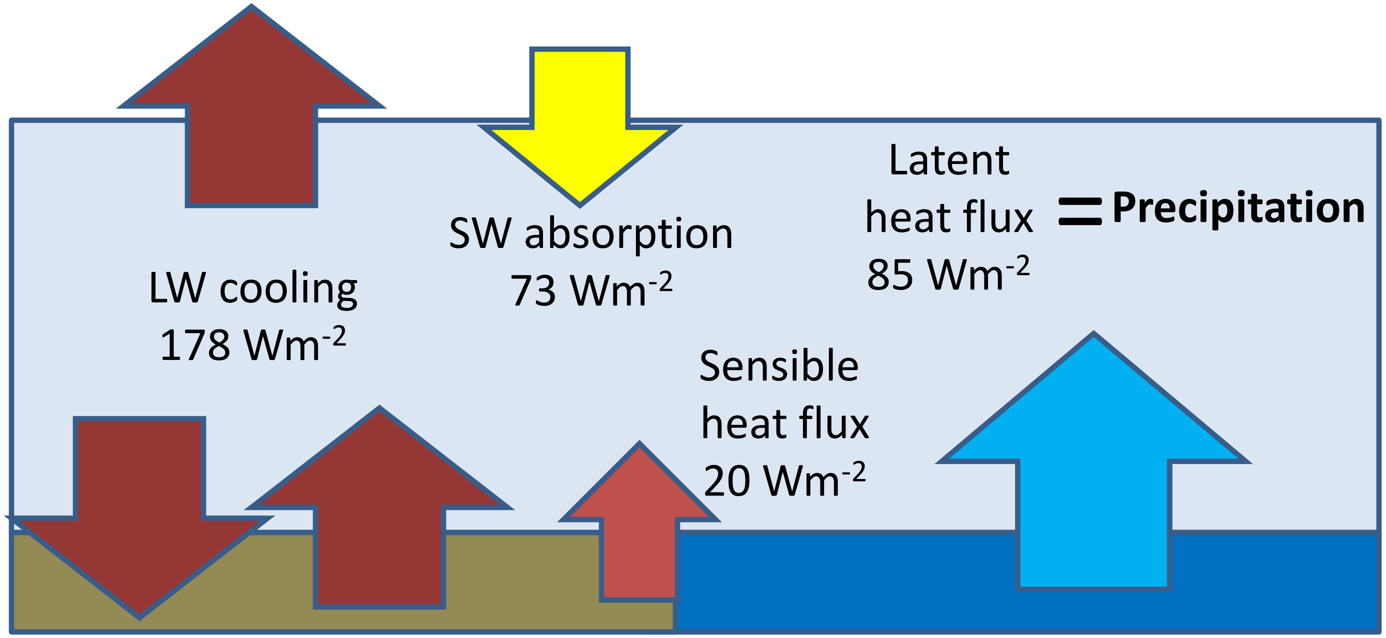
Precipitation increases at **1-3%/K**

Surface warming

Plot from Held and Soden (2006)

Precipitation as energy flux

Atmospheric
Energy
Budget



LW cooling
178 Wm^{-2}

SW absorption
73 Wm^{-2}

Latent
heat flux
85 Wm^{-2}

= **Precipitation**

Sensible
heat flux
20 Wm^{-2}

$$LW_{atm} - SW_{atm} - SH = LH$$

$$\Delta P \approx \Delta R_{atm} = \Delta LW_{atm} - \Delta SW_{atm}$$

The dominant factor controlling the global-mean precipitation increase with surface temperature increase is the clear-sky atmospheric radiation.

CMIP5 multi-model mean change

Transient CO_2 increase (1pctCO2)

$\Delta P/\Delta T$	**1.1**
Clear-sky $\Delta R_{atm}/\Delta T$	1.2
Total $\Delta R_{atm}/\Delta T$	0.8
Clouds	-0.4
$\Delta SH/\Delta T$	0.3 $Wm^{-2}K^{-1}$

Sign: positive corresponds
to increased precipitation

Approach

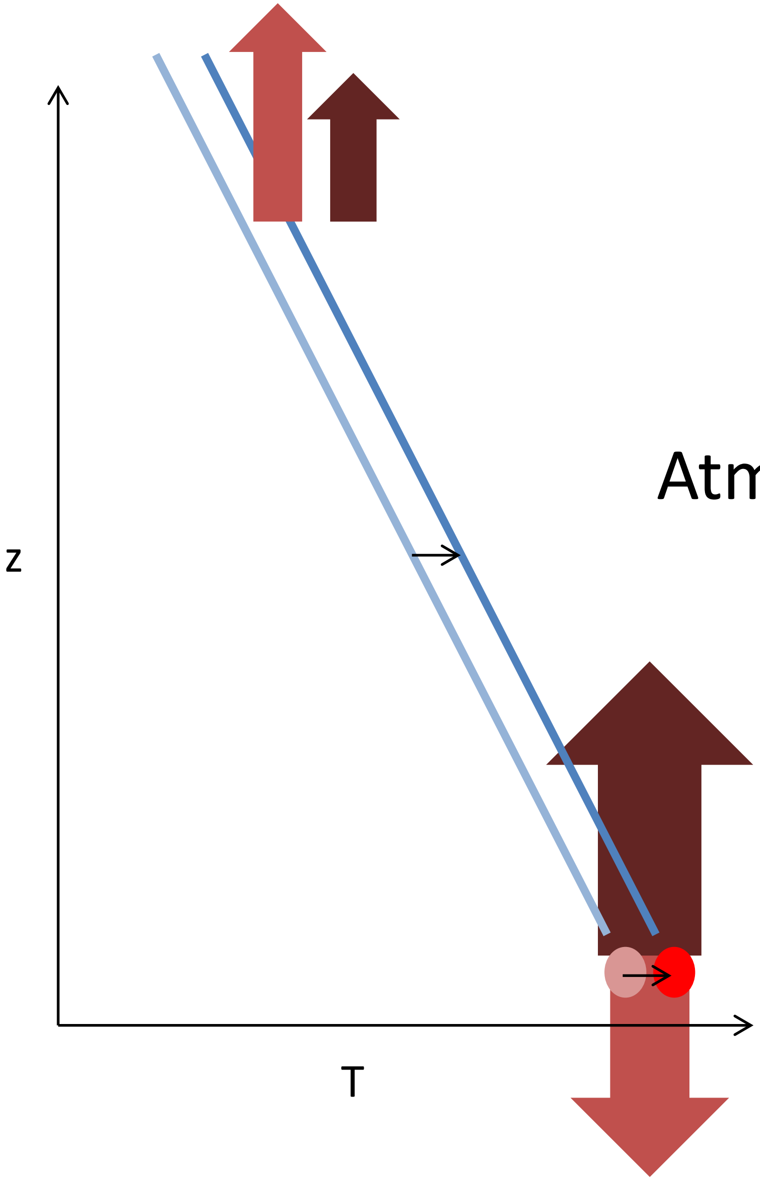
- Column radiation model (Fu and Liou 1992)
  - CMIP5 multi-model annual mean T, q profiles
- Make simple changes
  - Warm by 1 K
  - Moisten at constant RH
  - Vertically amplify warming
  - Increase CO_2
- Calculate clear-sky atmospheric radiative cooling response at each gridpoint – then take global mean

Goal

- Take what we know about the TOA radiative response (from climate feedbacks)

- Incorporate surface response to make it relevant to precipitation change

Warm the atmosphere and surface by 1 K



ΔT_a

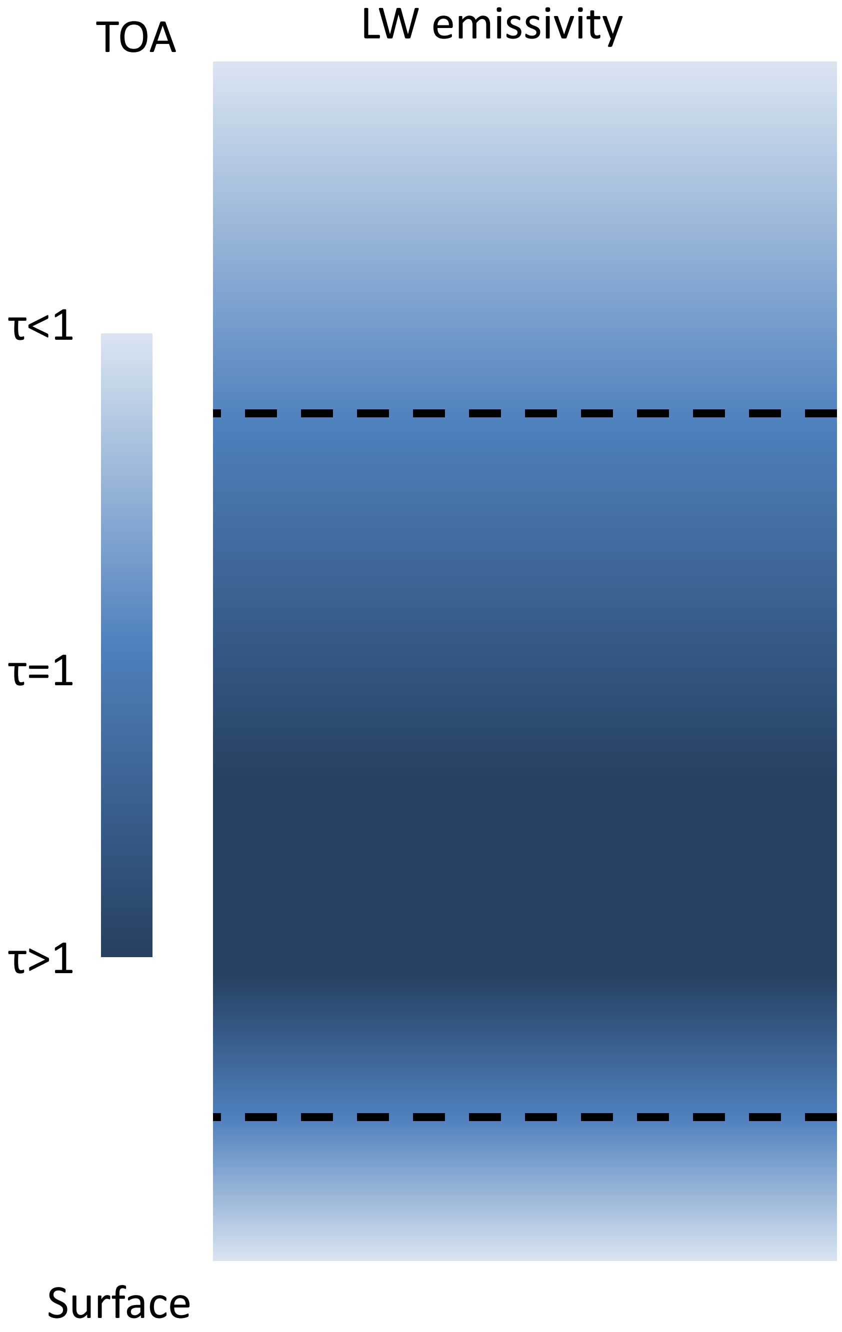
TOA $\Delta R_{\uparrow}$ = 2.0

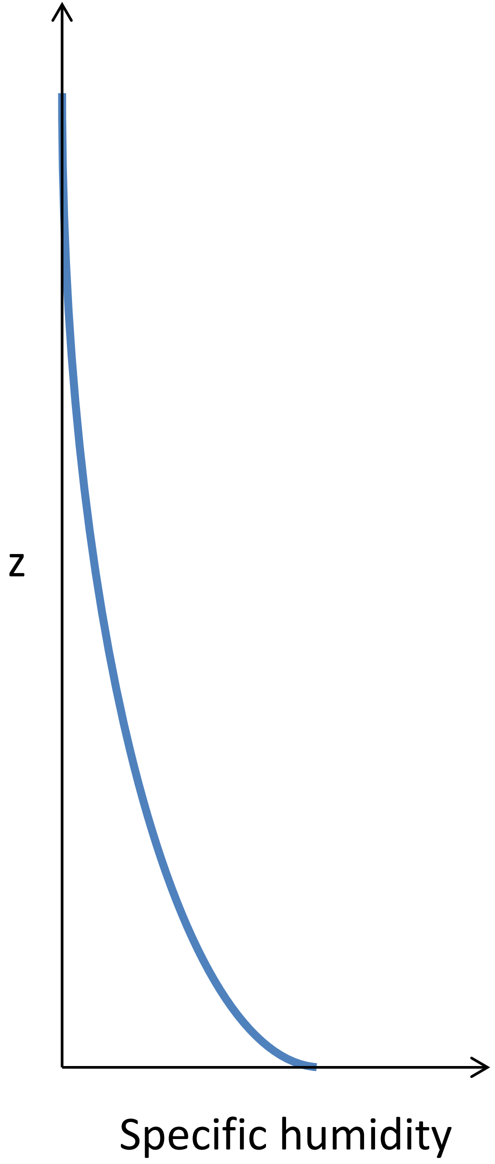
Atmosphere ΔR = 5.1

Surface $\Delta R_{\downarrow}$ = 3.0

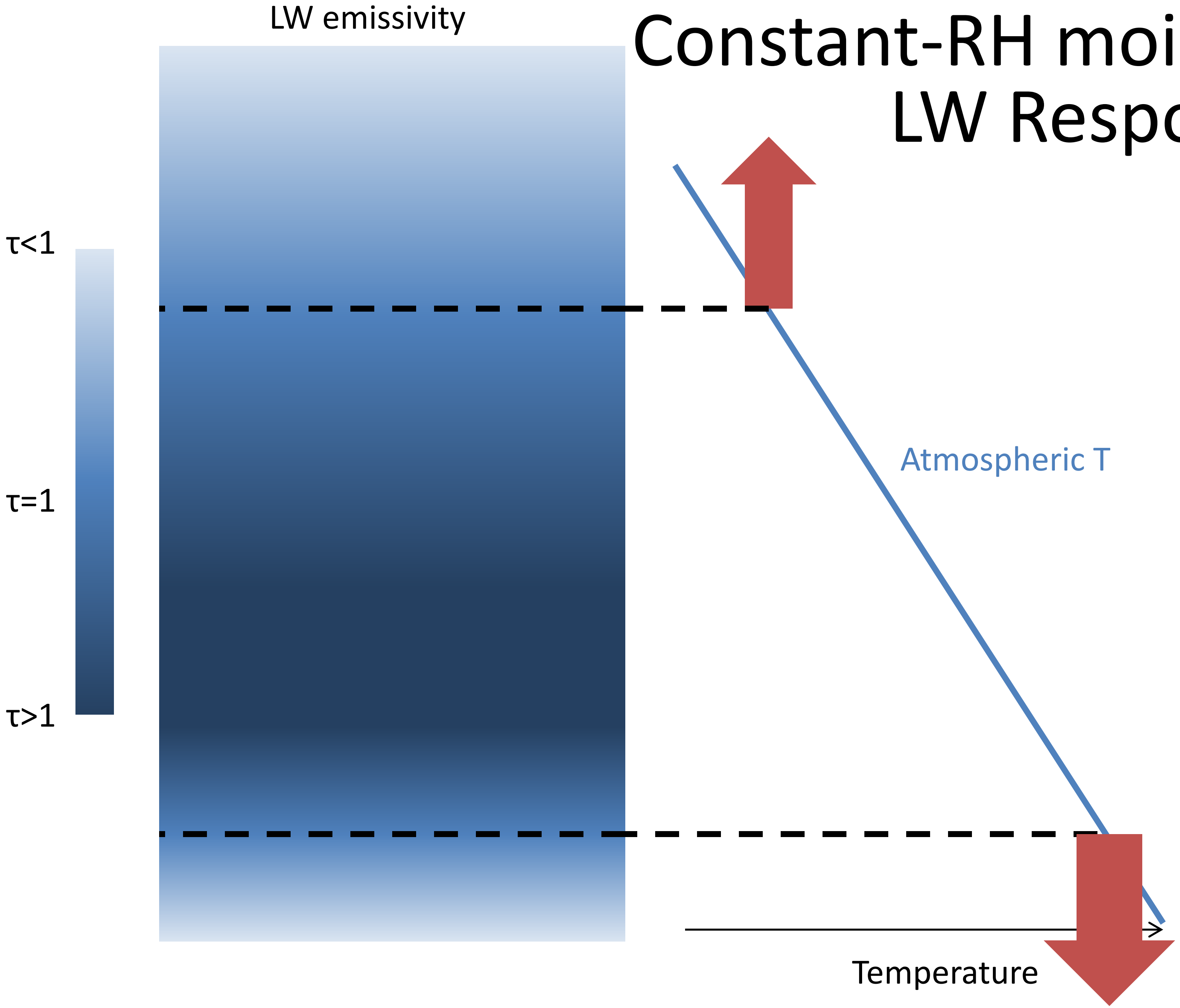
$$ATM = TOA_{\uparrow} + SFC_{\downarrow}$$

Constant-RH moisten LW Response

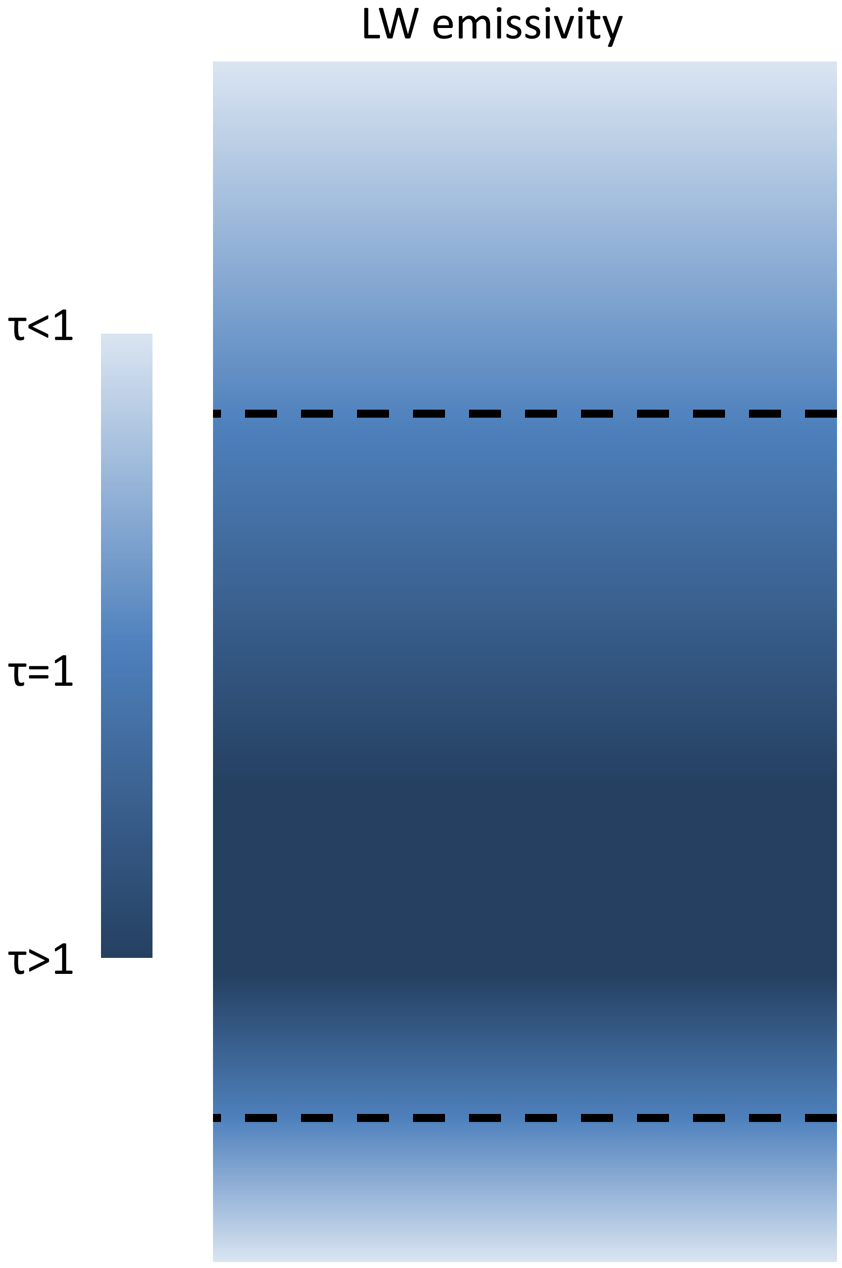


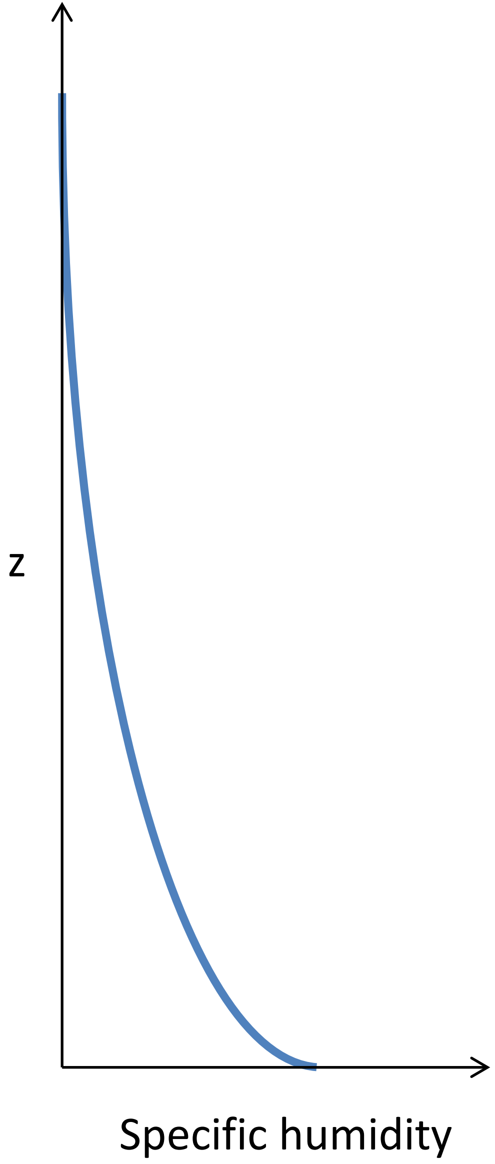


Constant-RH moisten
LW Response

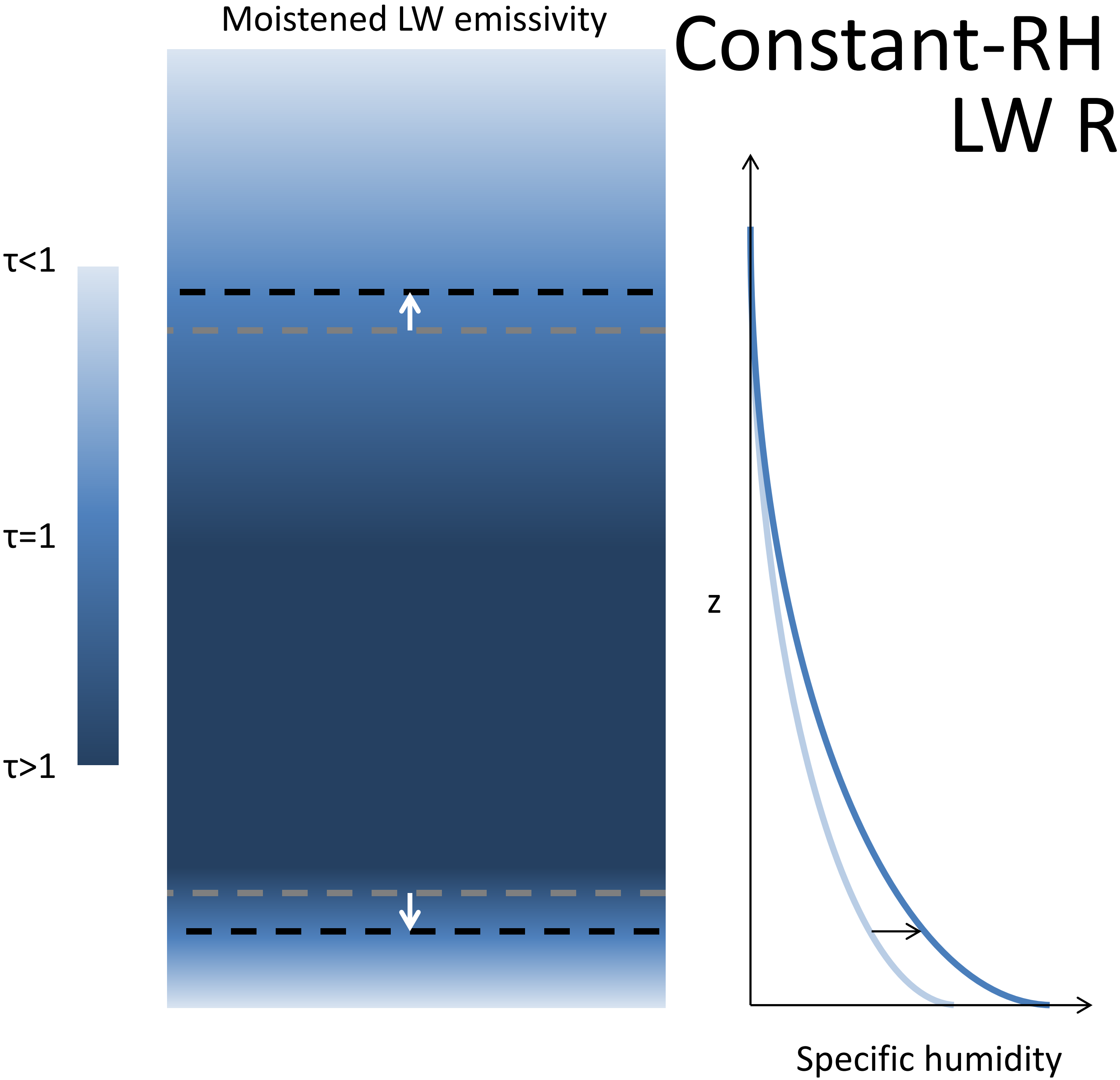


Constant-RH moisten LW Response

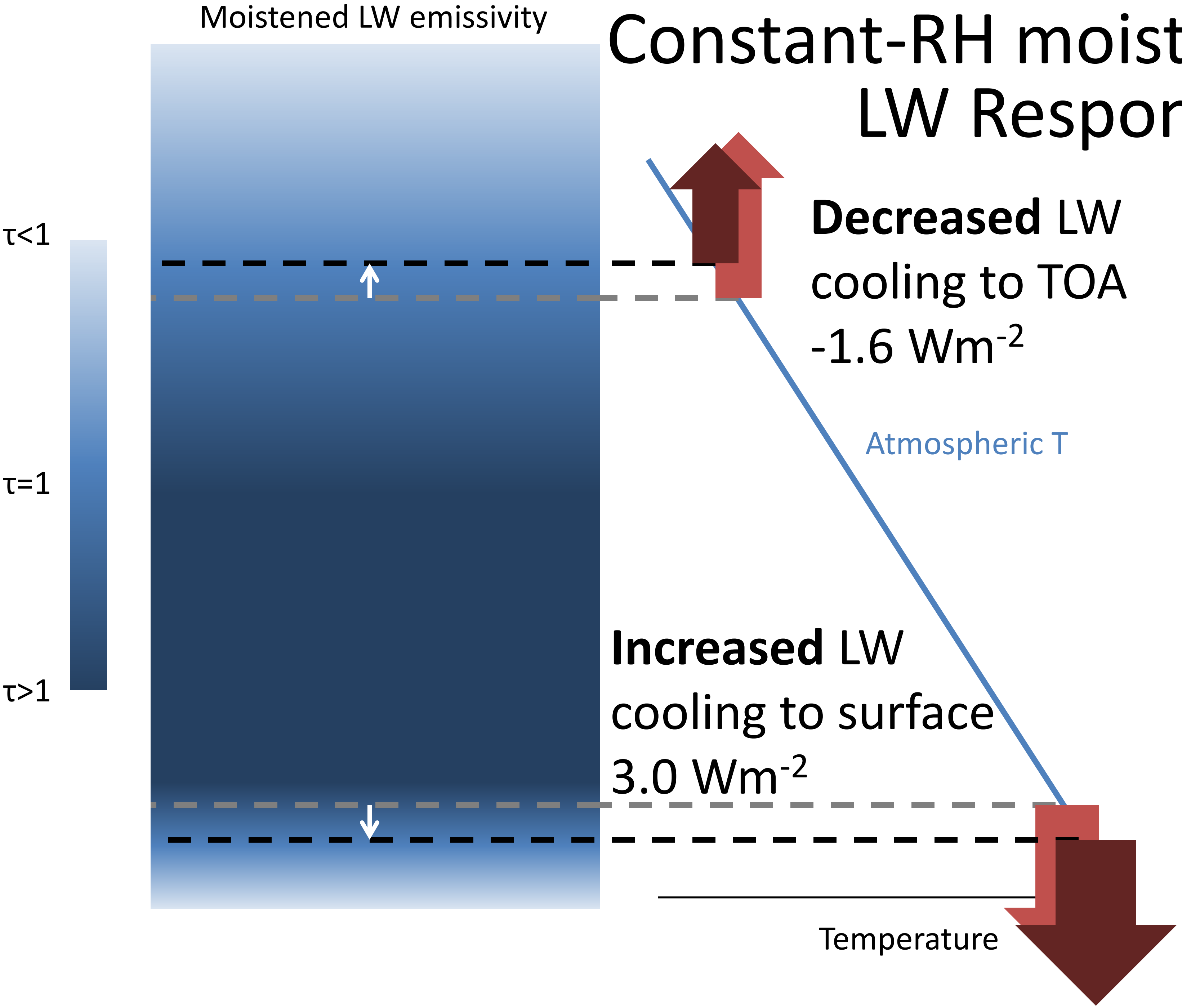




Constant-RH moisten
LW Response



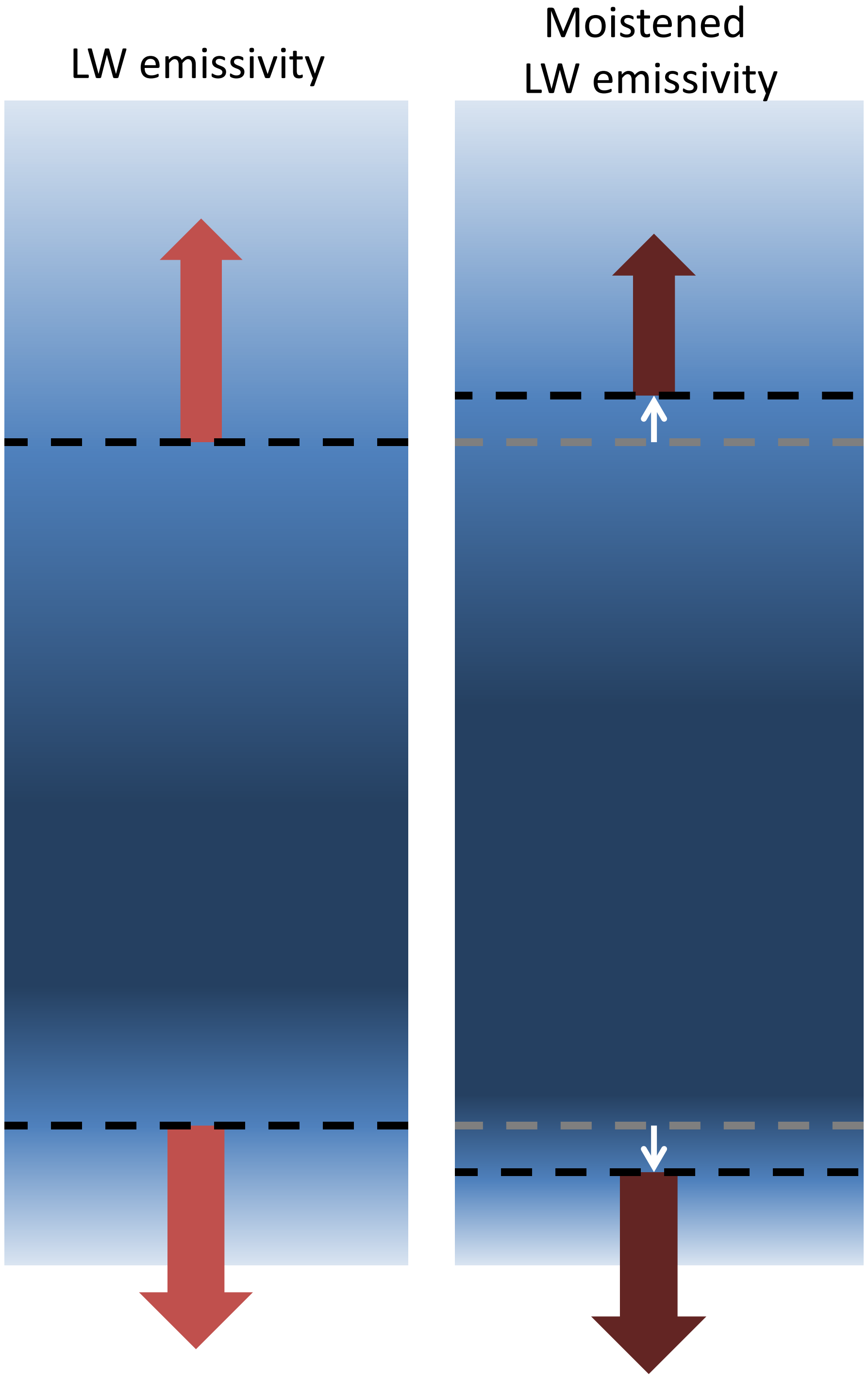
Constant-RH moisten LW Response



Decreased LW cooling to TOA $-1.6\ \mathrm{Wm^{-2}}$

Increased LW cooling to surface $3.0\ \mathrm{Wm^{-2}}$

Constant-RH moisten LW Response



TOA $\Delta R_{\uparrow}$= -1.6 $\mathrm{Wm^{-2}}$

Decreased LW cooling to TOA

Atmosphere ΔR: 1.5 $\mathrm{Wm^{-2}}$

Increased atmospheric LW cooling

Surface $\Delta R_{\downarrow}$: 3.0 $\mathrm{Wm^{-2}}$

Increased LW cooling to surface

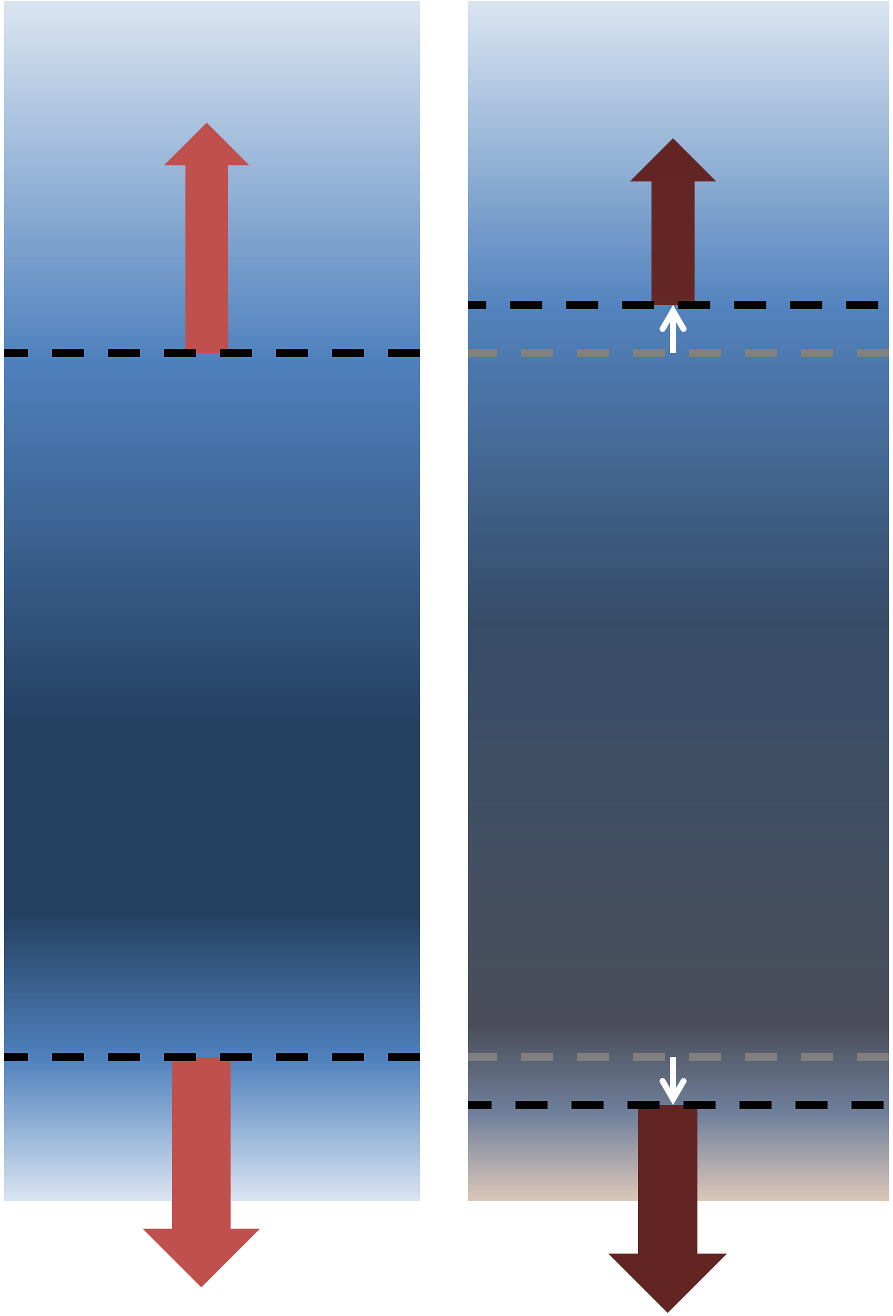
Constant-RH moisten SW Response

TOA $\Delta R_{\uparrow}$= -0.1 Wm^{-2}

Atmosphere ΔR: -0.9 Wm^{-2}

Surface $\Delta R_{\downarrow}$: -0.8 Wm^{-2}

Constant-RH moisten LW+SW Response

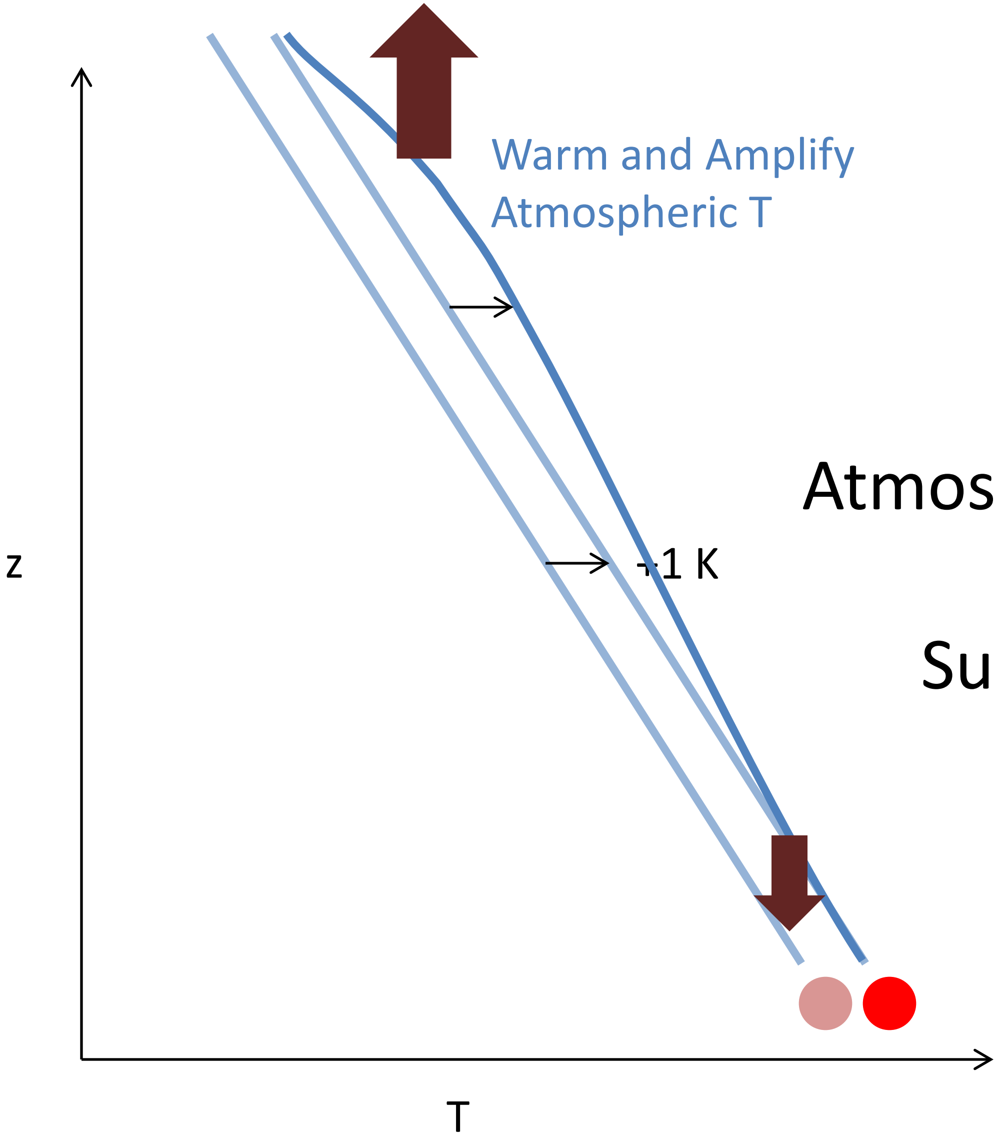


TOA $\Delta R_{\uparrow}$= -1.7 Wm^{-2}

Atmosphere ΔR: 0.6 Wm^{-2}

Surface $\Delta R_{\downarrow}$: 2.2 Wm^{-2}

Lapse rate change



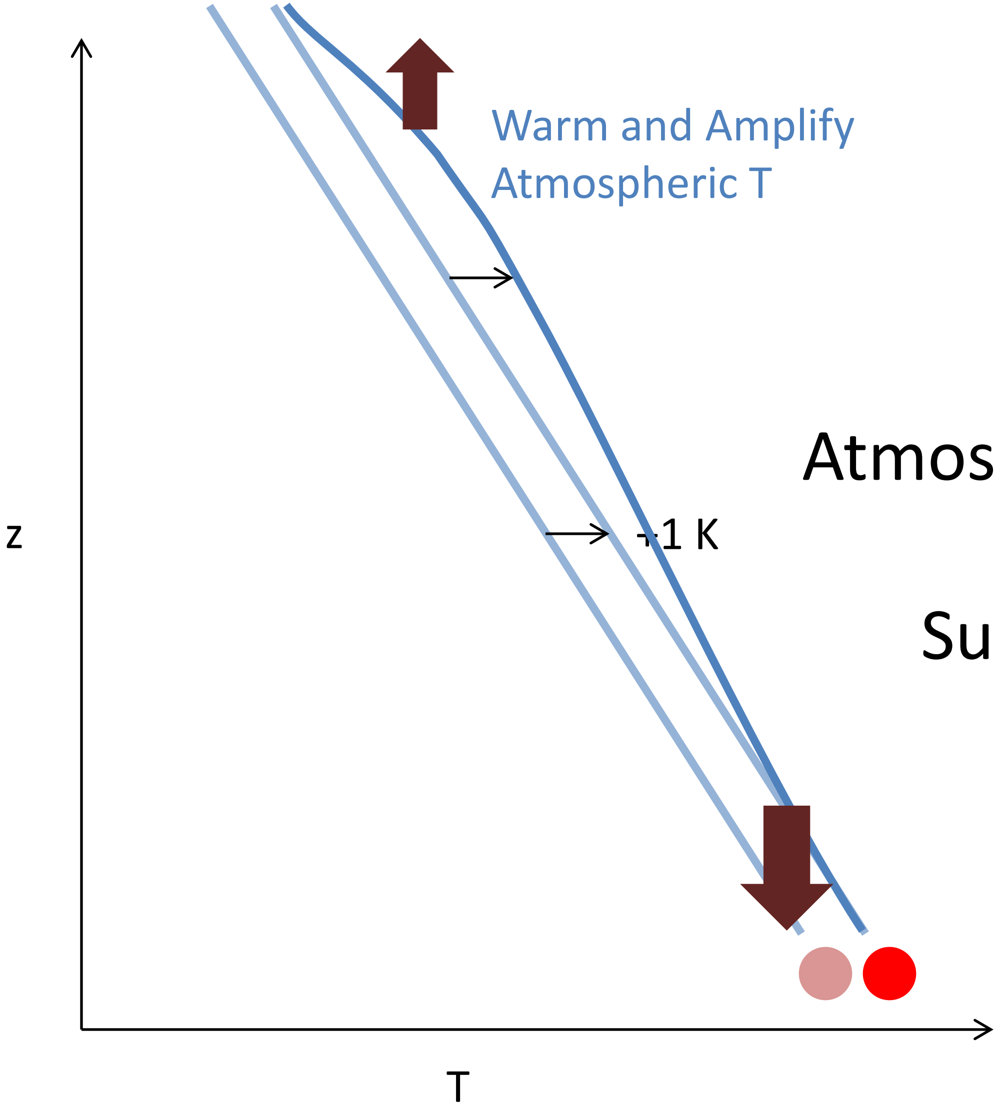
ΔT

TOA $\Delta R_{\uparrow}$ = 0.9

Atmosphere ΔR = 1.1

Surface $\Delta R_{\downarrow}$ = 0.2

Lapse rate change

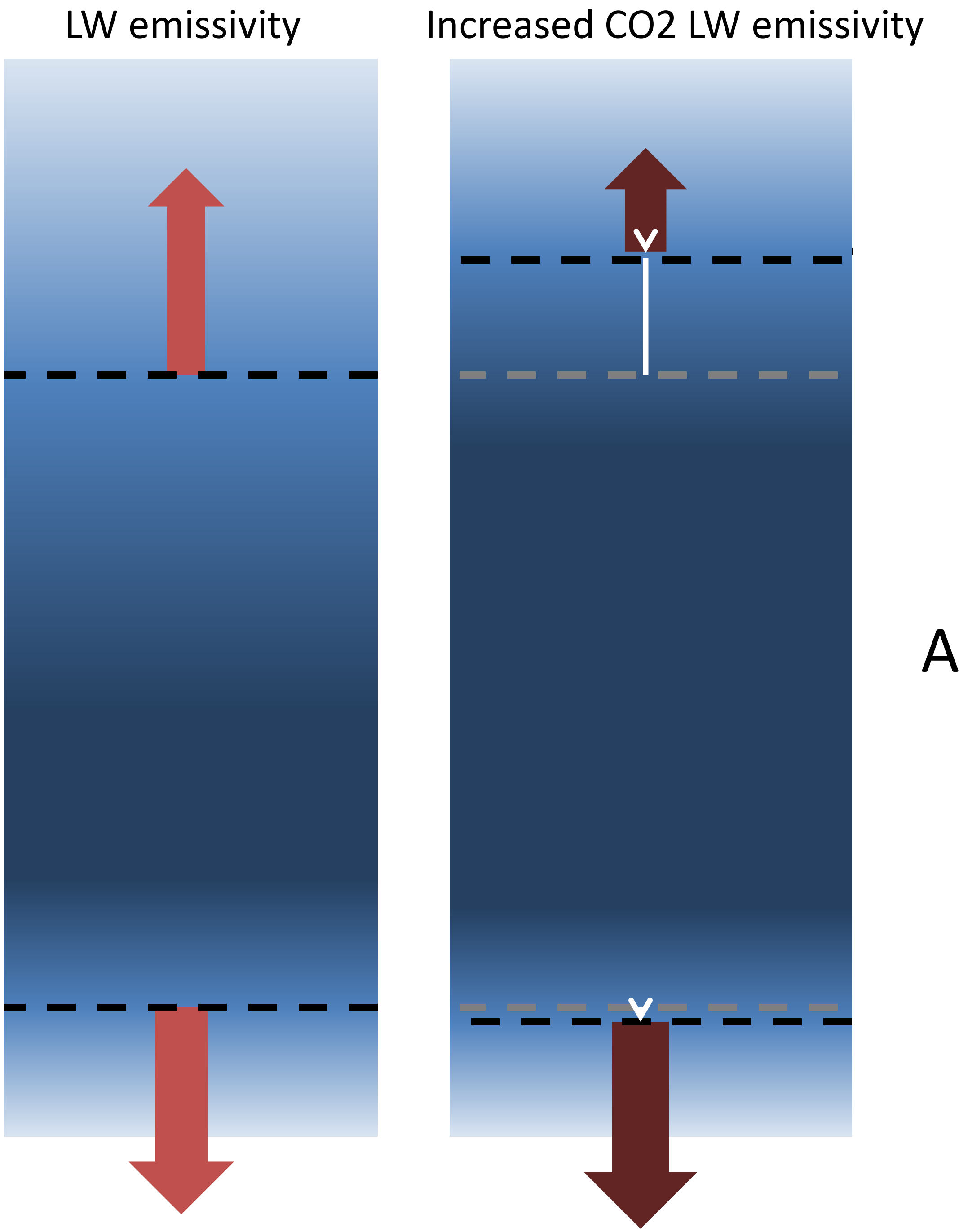


	ΔT	$\Delta T+\Delta q$
TOA $\Delta R_{\uparrow}$ =	0.9	0.1 Wm^{-2}
Atmosphere ΔR =	1.1	0.5 Wm^{-2}
Surface $\Delta R_{\downarrow}$ =	0.2	0.4 Wm^{-2}

CO_2 Forcing

Chosen to match GCM TOA transient imbalance

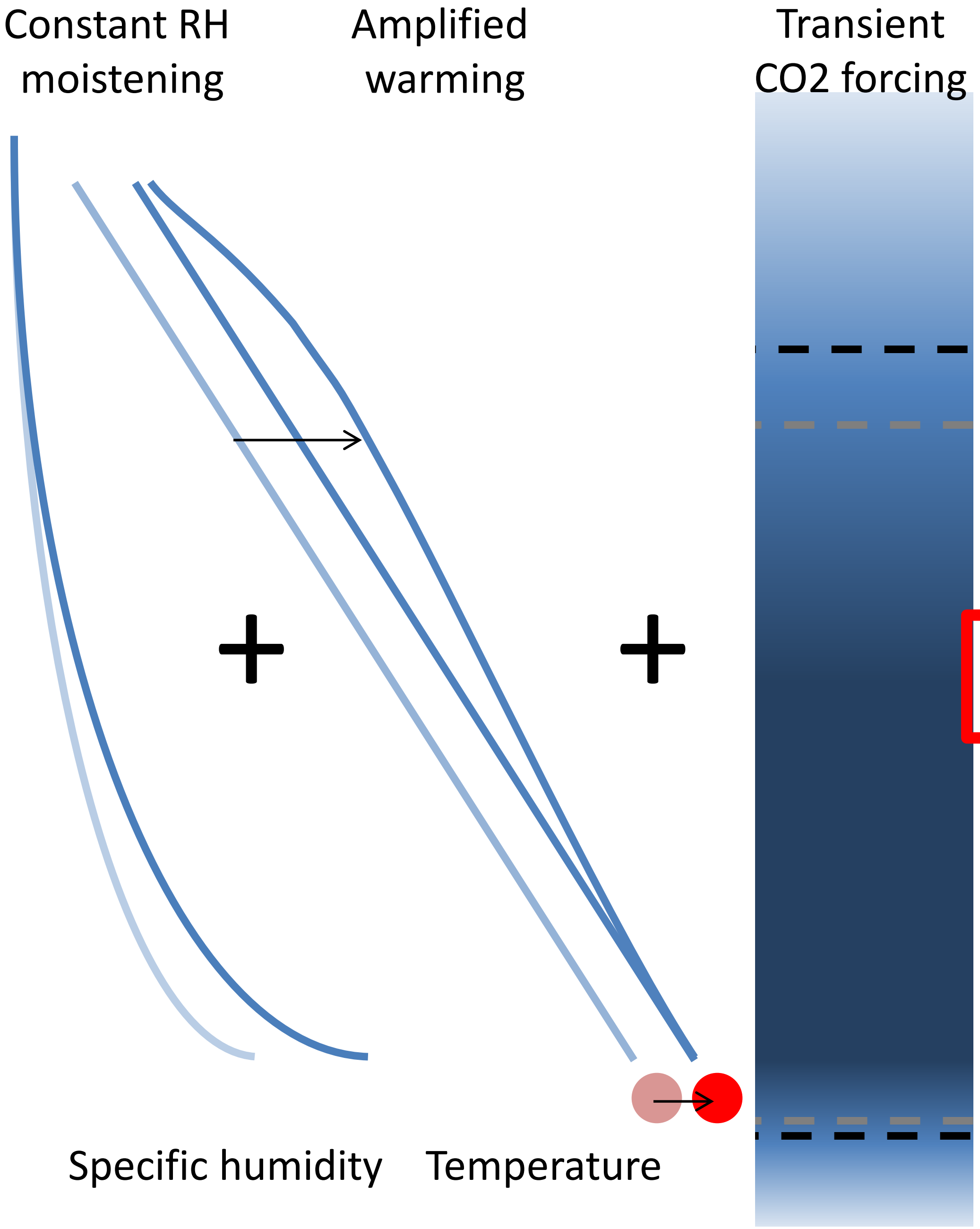
TOA $\Delta R_{\uparrow} = -2.4\ Wm^{-2}$



Atmosphere ΔR: $-1.3\ Wm^{-2}$

Surface $\Delta R_{\downarrow}$: $1.1\ Wm^{-2}$

Total



TOA $\Delta R_{\uparrow} = -0.7\ \mathrm{Wm}^{-2}$

Atmosphere ΔR: **1.0** Wm^{-2}

Surface $\Delta R_{\downarrow}$: $1.7\ \mathrm{Wm}^{-2}$

Clear-sky atmospheric column calculation

$\Delta R_{atm}/\Delta T$	1.0 $Wm^{-2}K^{-1}$

CMIP5 multi-model mean

$\Delta P/\Delta T$	1.1
Clear-sky $\Delta R_{atm}/\Delta T$	1.2
Total $\Delta R_{atm}/\Delta T$	0.8
Clouds	-0.4
$\Delta SH/\Delta T$	0.3 $Wm^{-2}K^{-1}$

Positive corresponds to increased precipitation

Part 1: Key points

- Clear-sky atmospheric radiative cooling responses calculated with a column radiation model correctly predicts the global-mean precipitation change in CMIP5 models.

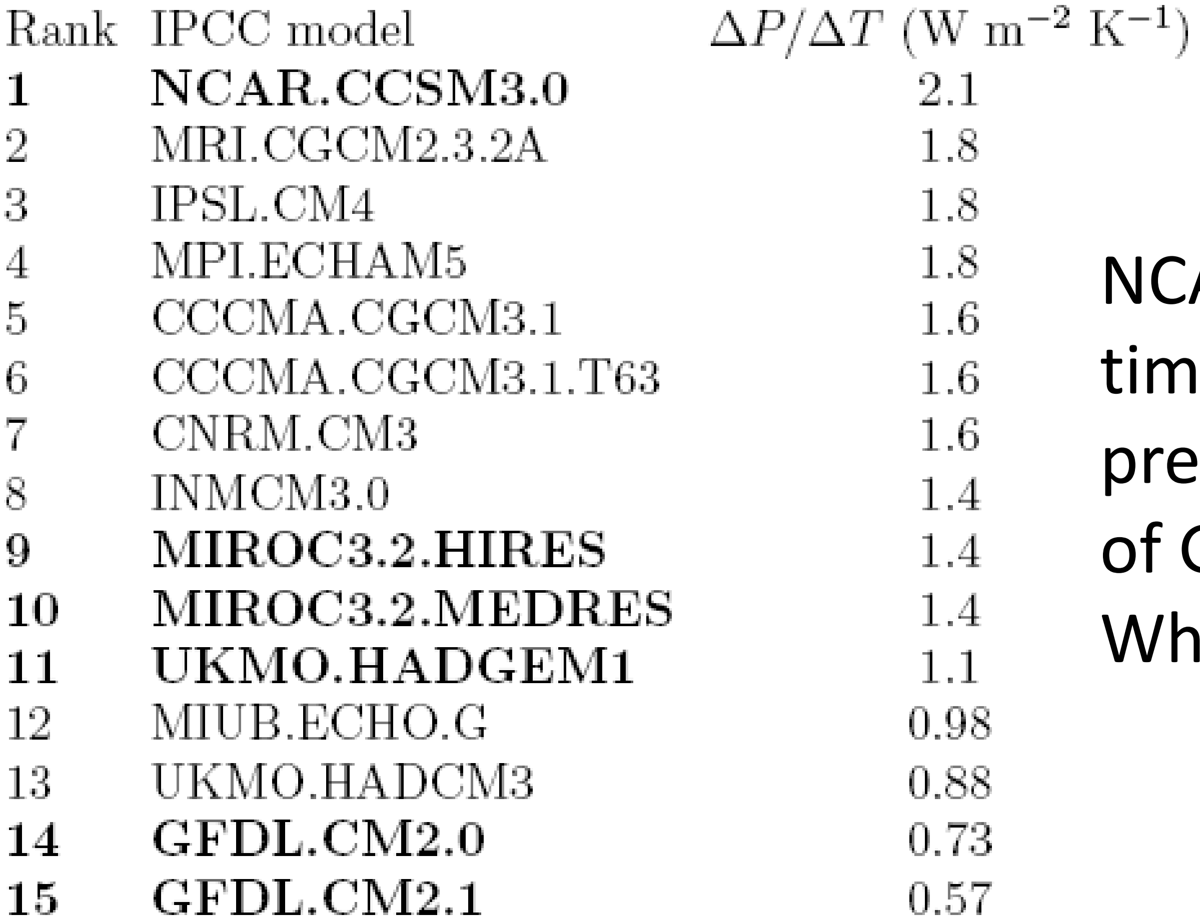
- The change in the surface flux, especially due to moistening, is critically important in determining the precipitation response to warming.

- You can infer precipitation responses of the wrong sign by considering only the top-of-atmosphere radiation.

Pendergrass, A.G. and D.L. Hartmann (2012). *GRL*.

GLOBAL-MEAN PRECIPITATION AND BLACK CARBON IN AR4 SIMULATIONS

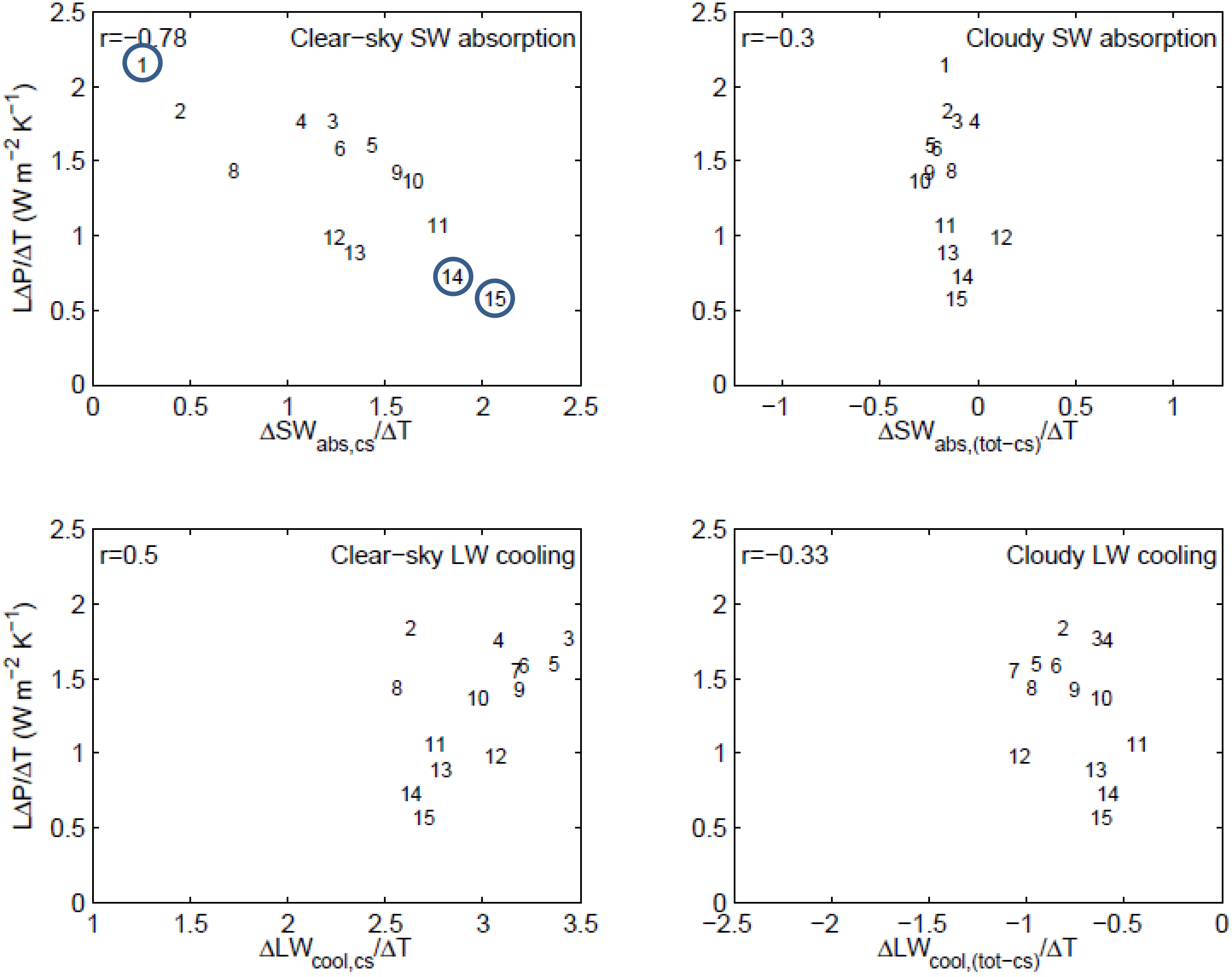
A1b forcing scenario: greenhouse gases and aerosols



Rank	IPCC model	$\Delta P/\Delta T$ (W m^{-2} K^{-1})
1	**NCAR.CCSM3.0**	2.1
2	MRI.CGCM2.3.2A	1.8
3	IPSL.CM4	1.8
4	MPI.ECHAM5	1.8
5	CCCMA.CGCM3.1	1.6
6	CCCMA.CGCM3.1.T63	1.6
7	CNRM.CM3	1.6
8	INMCM3.0	1.4
9	**MIROC3.2.HIRES**	1.4
10	**MIROC3.2.MEDRES**	1.4
11	**UKMO.HADGEM1**	1.1
12	MIUB.ECHO.G	0.98
13	UKMO.HADCM3	0.88
14	**GFDL.CM2.0**	0.73
15	**GFDL.CM2.1**	0.57

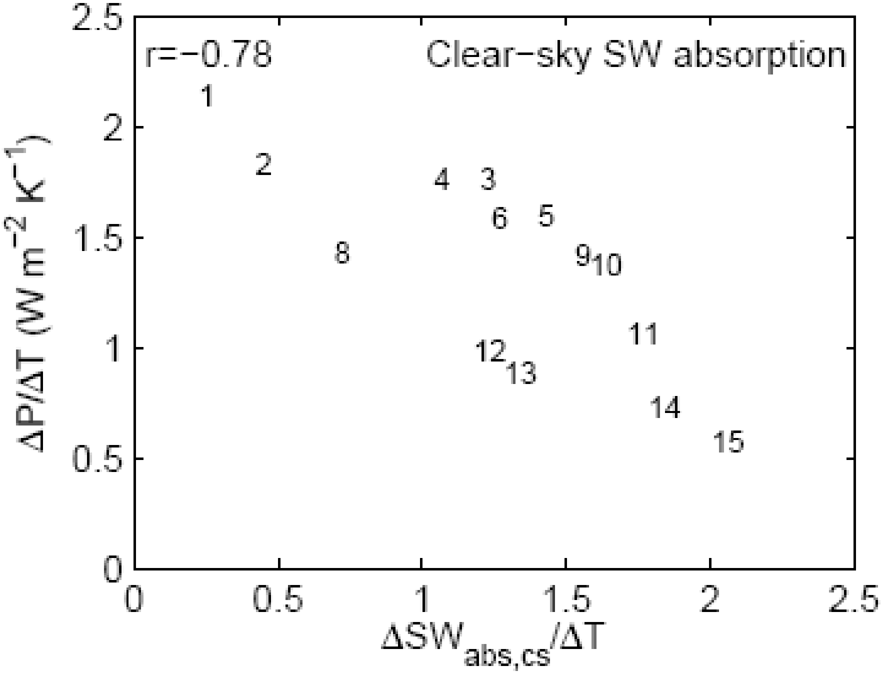
NCAR has almost 4 times the precipitation change of GFDL CM2.1! Why?

LW/SW clear-sky/cloudy-sky changes and precipitation

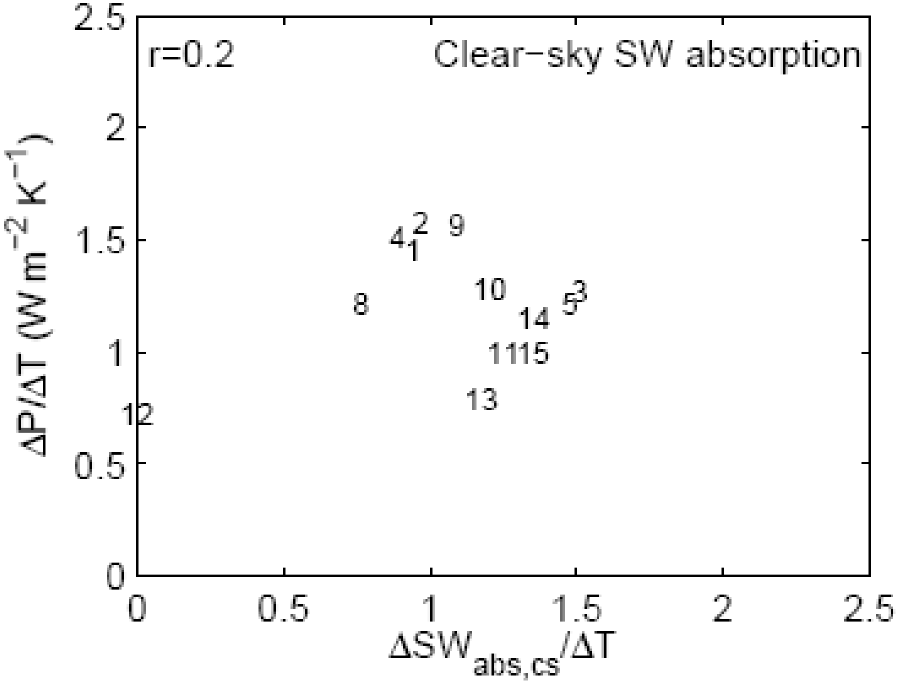


Shortwave absorption and precipitation without aerosol changes

A1b
(**with** aerosol changes)



1%/year to 2xCO_2
(**without** aerosol changes)



IPCC AR4 WG1
Meehl et al (2007)

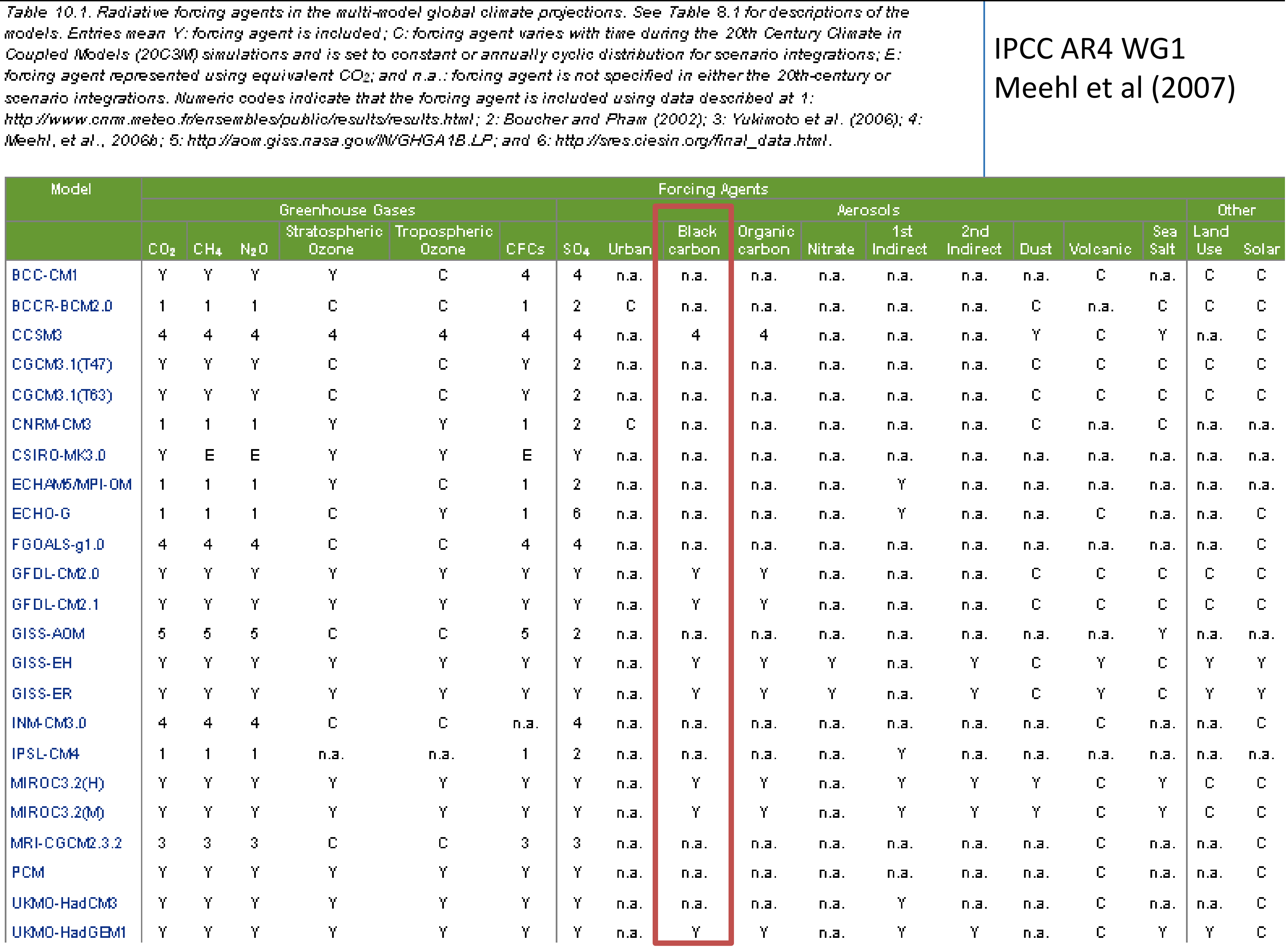
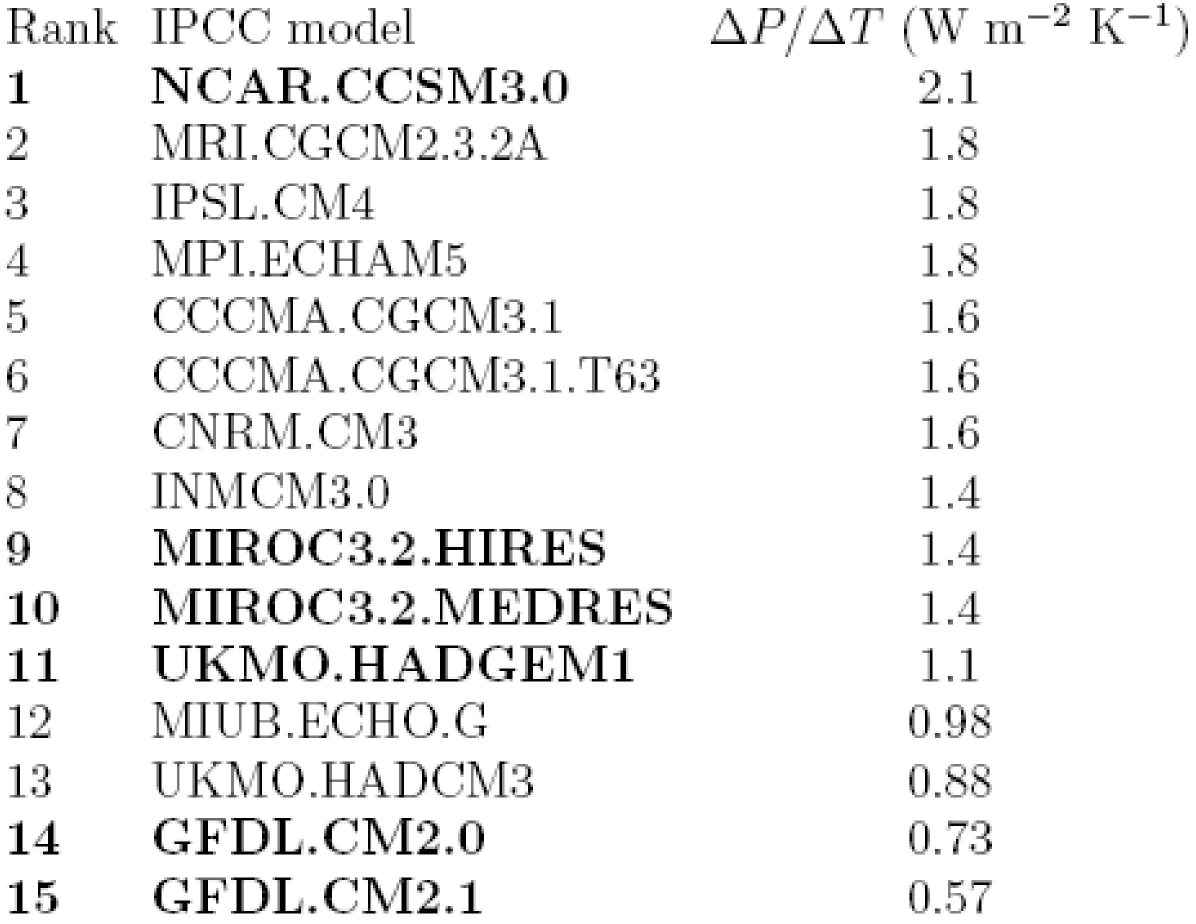


Table 10.1. Radiative forcing agents in the multi-model global climate projections. See Table 8.1 for descriptions of the models. Entries mean Y: forcing agent is included; C: forcing agent varies with time during the 20th Century Climate in Coupled Models (20C3M) simulations and is set to constant or annually cyclic distribution for scenario integrations; E: forcing agent represented using equivalent CO$_2$; and n.a.: forcing agent is not specified in either the 20th-century or scenario integrations. Numeric codes indicate that the forcing agent is included using data described at 1: http://www.cnrm.meteo.fr/ensembles/public/results/results.html; 2: Boucher and Pham (2002); 3: Yukimoto et al. (2006); 4: Meehl, et al., 2006b; 5: http://aom.giss.nasa.gov/IN/GHGA1B.LP; and 6: http://sres.ciesin.org/final_data.html.

Model	Forcing Agents																	
	Greenhouse Gases						Aerosols										Other	
	CO_2	CH_4	N_2O	Stratospheric Ozone	Tropospheric Ozone	CFCs	SO_4	Urban	Black carbon	Organic carbon	Nitrate	1st Indirect	2nd Indirect	Dust	Volcanic	Sea Salt	Land Use	Solar
BCC-CM1	Y	Y	Y	Y	C	4	4	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	C	n.a.	C	C
BCCR-BCM2.0	1	1	1	C	C	1	2	C	n.a.	n.a.	n.a.	n.a.	n.a.	C	n.a.	C	C	C
CCSM3	4	4	4	4	4	4	4	n.a.	4	4	n.a.	n.a.	n.a.	Y	C	Y	n.a.	C
CGCM3.1(T47)	Y	Y	Y	C	C	Y	2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	C	C	C	C	C
CGCM3.1(T63)	Y	Y	Y	C	C	Y	2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	C	C	C	C	C
CNRM-CM3	1	1	1	Y	Y	1	2	C	n.a.	n.a.	n.a.	n.a.	n.a.	C	n.a.	C	n.a.	n.a.
CSIRO-MK3.0	Y	E	E	Y	Y	E	Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
ECHAM5/MPI-OM	1	1	1	Y	C	1	2	n.a.	n.a.	n.a.	n.a.	Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
ECHO-G	1	1	1	C	Y	1	6	n.a.	n.a.	n.a.	n.a.	Y	n.a.	n.a.	C	n.a.	n.a.	C
FGOALS-g1.0	4	4	4	C	C	4	4	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	C
GFDL-CM2.0	Y	Y	Y	Y	Y	Y	Y	n.a.	Y	Y	n.a.	n.a.	n.a.	C	C	C	C	C
GFDL-CM2.1	Y	Y	Y	Y	Y	Y	Y	n.a.	Y	Y	n.a.	n.a.	n.a.	C	C	C	C	C
GISS-AOM	5	5	5	C	C	5	2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Y	n.a.	n.a.
GISS-EH	Y	Y	Y	Y	Y	Y	Y	n.a.	Y	Y	Y	n.a.	Y	C	Y	C	Y	Y
GISS-ER	Y	Y	Y	Y	Y	Y	Y	n.a.	Y	Y	Y	n.a.	Y	C	Y	C	Y	Y
INM-CM3.0	4	4	4	C	C	n.a.	4	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	C	n.a.	n.a.	C
IPSL-CM4	1	1	1	n.a.	n.a.	1	2	n.a.	n.a.	n.a.	n.a.	Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
MIROC3.2(H)	Y	Y	Y	Y	Y	Y	Y	n.a.	Y	Y	n.a.	Y	Y	Y	C	Y	C	C
MIROC3.2(M)	Y	Y	Y	Y	Y	Y	Y	n.a.	Y	Y	n.a.	Y	Y	Y	C	Y	C	C
MRI-CGCM2.3.2	3	3	3	C	C	3	3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	C	n.a.	n.a.	C
PCM	Y	Y	Y	Y	Y	Y	Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	C	n.a.	n.a.	C
UKMO-HadCM3	Y	Y	Y	Y	Y	Y	Y	n.a.	n.a.	n.a.	n.a.	Y	n.a.	n.a.	C	n.a.	n.a.	C
UKMO-HadGEM1	Y	Y	Y	Y	Y	Y	Y	n.a.	Y	Y	n.a.	Y	Y	n.a.	C	Y	Y	C

AR4 models, black carbon forcing, and 21^{st} Century precipitation change



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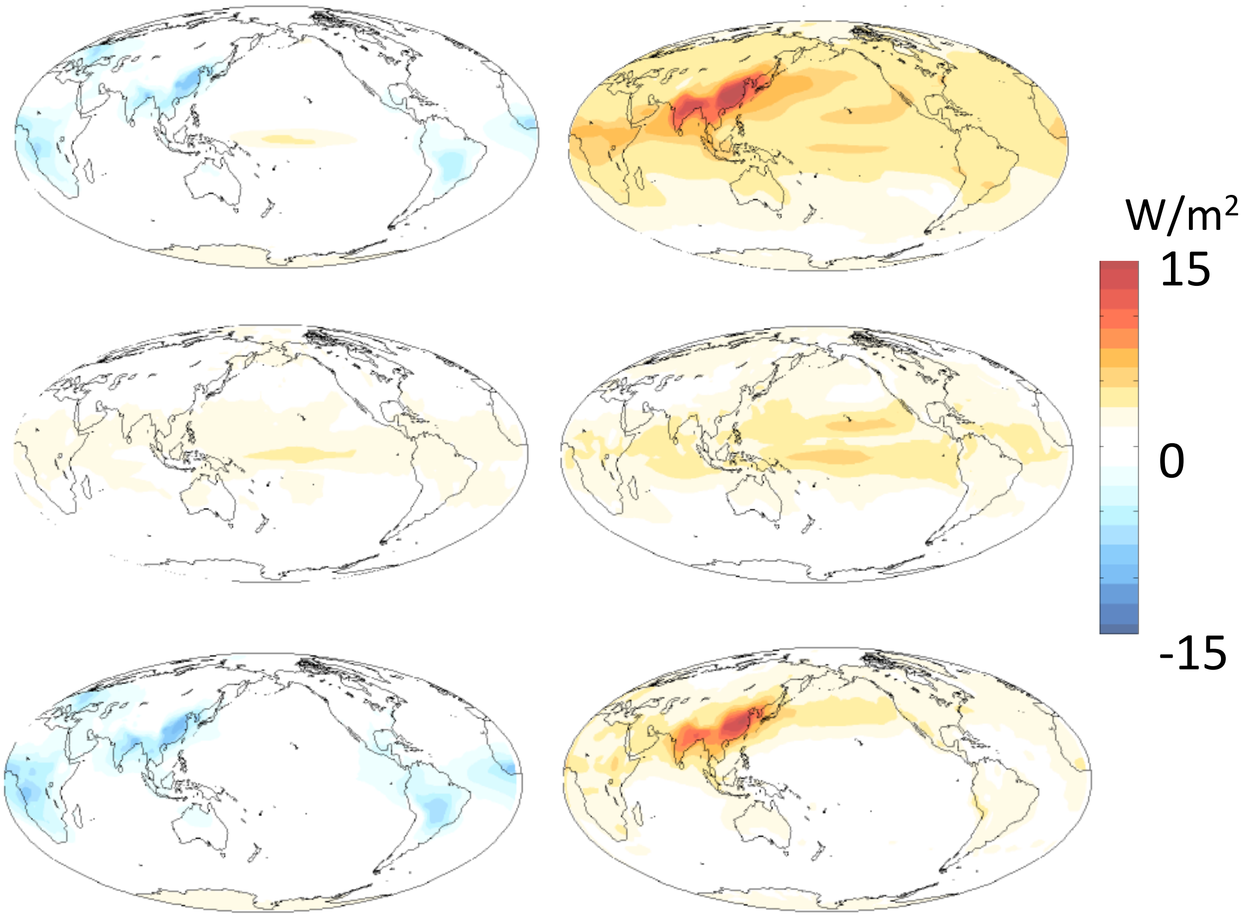
Bolded models incorporate black carbon forcing (IPCC Table 10.1).

Clear-sky shortwave atmospheric absorption change

NCAR CCSM 3.0

GFDL CM 2.0



Change in clear-sky shortwave absorption

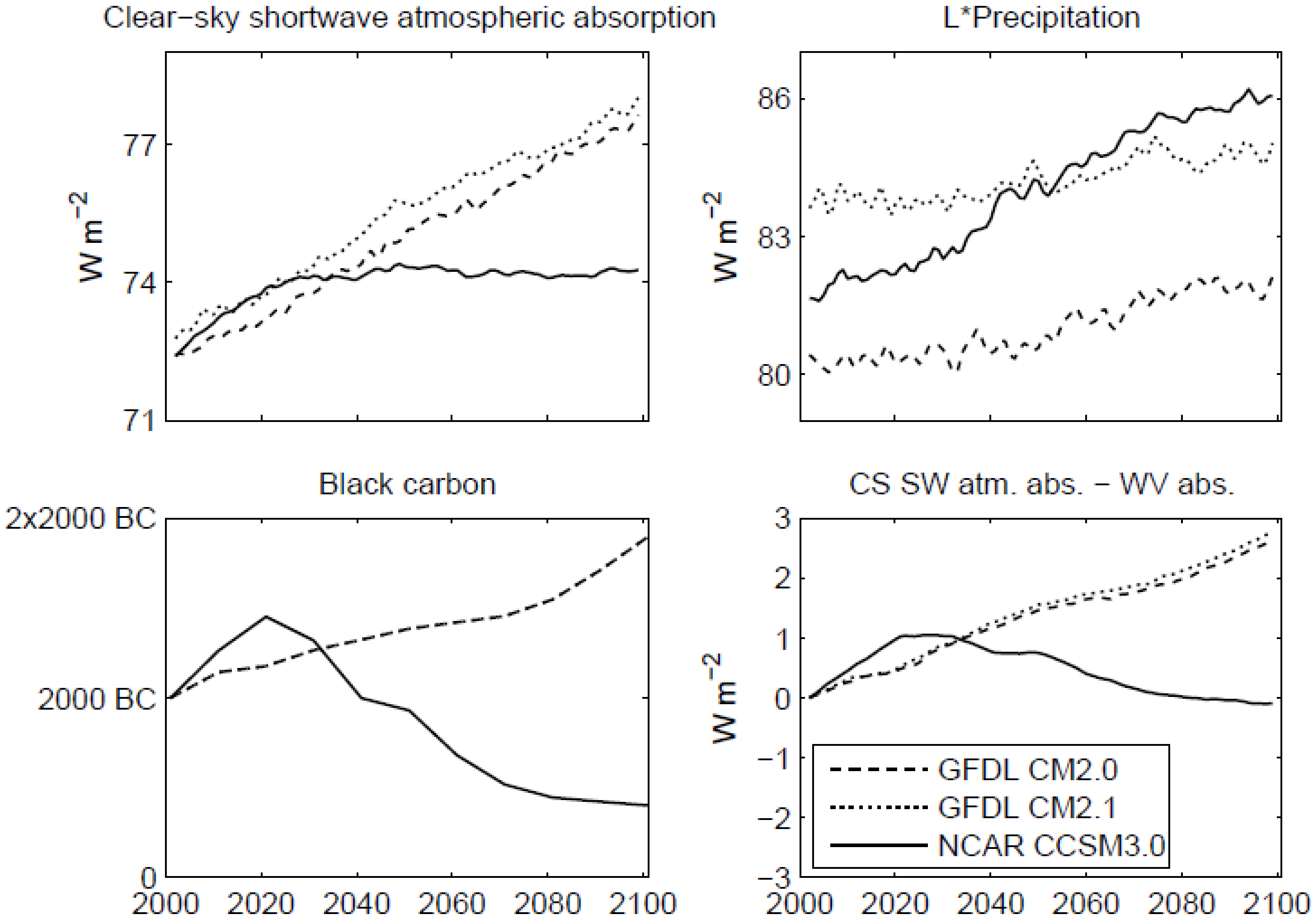
Part due to absorption by water vapor (using feedback kernels from Previdi [2010])

Difference of above

Precipitation and black carbon forcing timeseries

NCAR CCSM 3:
BC concentration timeseries tied to sulfate aerosol (Meehl et al 2006)

GFDL CM 2:
BC emission timeseries tied to CO (Horowitz et al 2003, Horowitz 2006, Levy et al 2008)



Clear-sky SW absorption and precipitation respond to variations in black carbon forcing.

Conclusions: Part 2

- Different black carbon forcing prescriptions in A1b simulations in AR4 impact the atmospheric energy budget and affect global-mean precipitation.

- Clear-sky SW atmospheric absorption forcing varies by 1.9 $Wm^{-2}K^{-1}$ across IPCC AR4 A1b models, which in turn affects global mean precipitation by 1.5 $Wm^{-2}K^{-1}$, or 1.9 cm $y^{-1}K^{-1}$.

- Better characterization of aerosol radiative properties is required for intercomparison studies of model precipitation changes.

Take home messages

- Global-mean precipitation in model experiments is balanced by changes in clear-sky atmospheric radiative cooling
- Moistening decreases OLR but increases LW emission to the surface
- Black carbon is an efficient forcing agent on precipitation

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Acknowledgements

- Funding provided by NSF grant AGS-0960497.

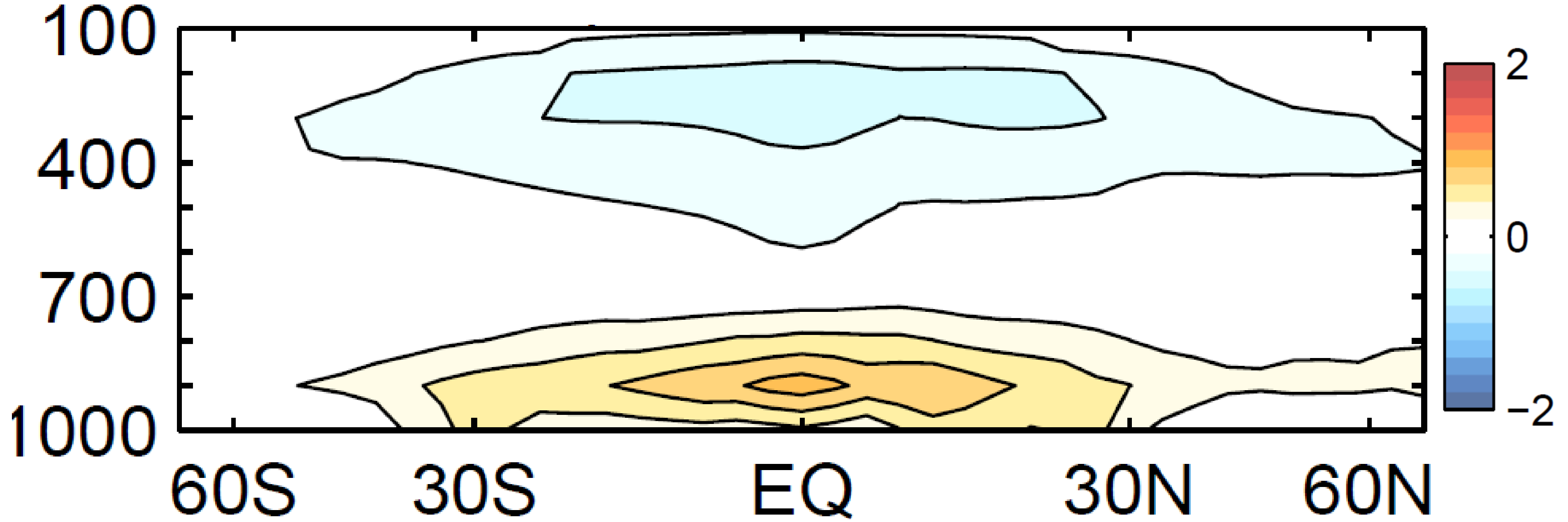
- CMIP5 modeling groups provided a wealth of data, managed by PCMDI at LLNL.

- Bryce Harrop provided calculations of the insolation-weighted annual mean solar zenith angle.

- Michael Previdi provided radiative feedback kernels.

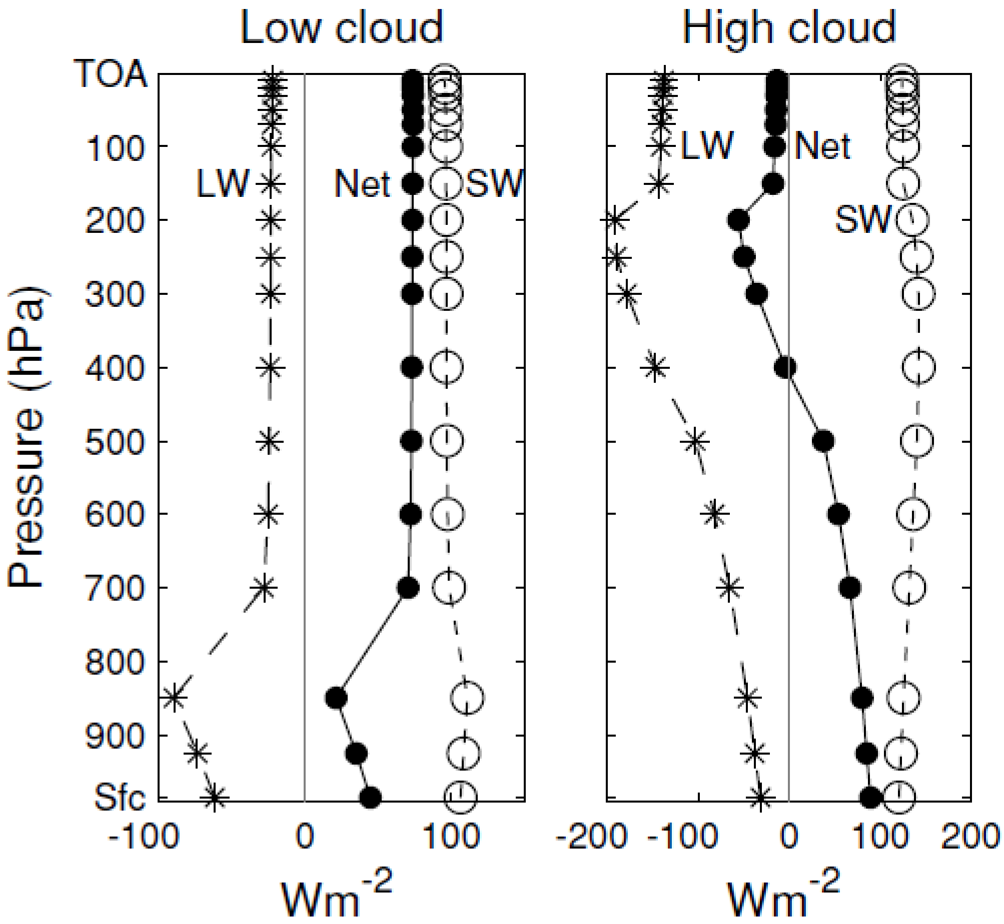
Extra slides

LW water vapor



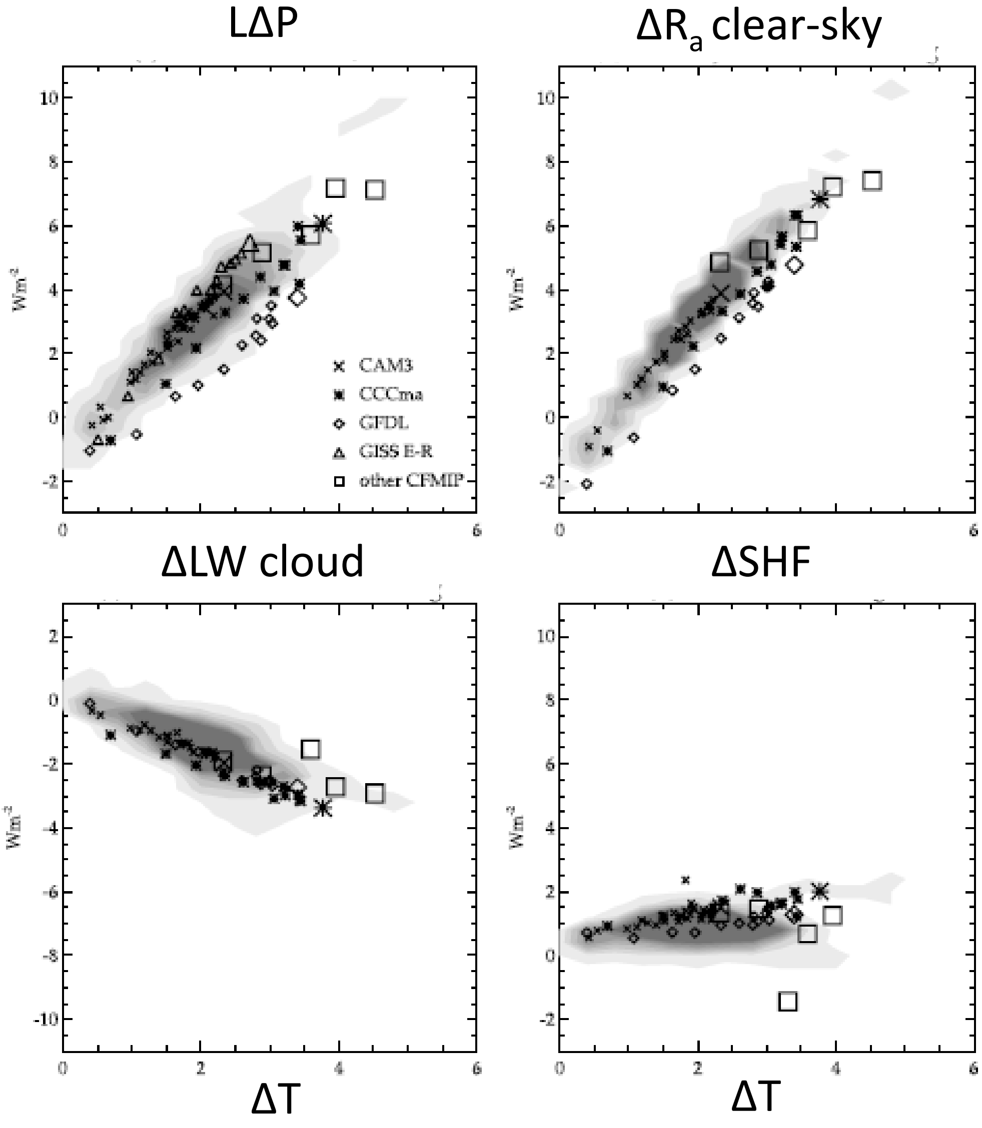
Atmospheric cooling increase due to the CMIP5 specific humidity change at each lon, pressure $[\mathrm{Wm^{-2}K^{-1}(100\ hPa)^{-1}}]$

Upwelling radiative flux due to idealized clouds



Previous work: Lambert and Webb (2008)

- Examined a perturbed physics GCM ensemble
- Found clear-sky radiation of fundamental importance



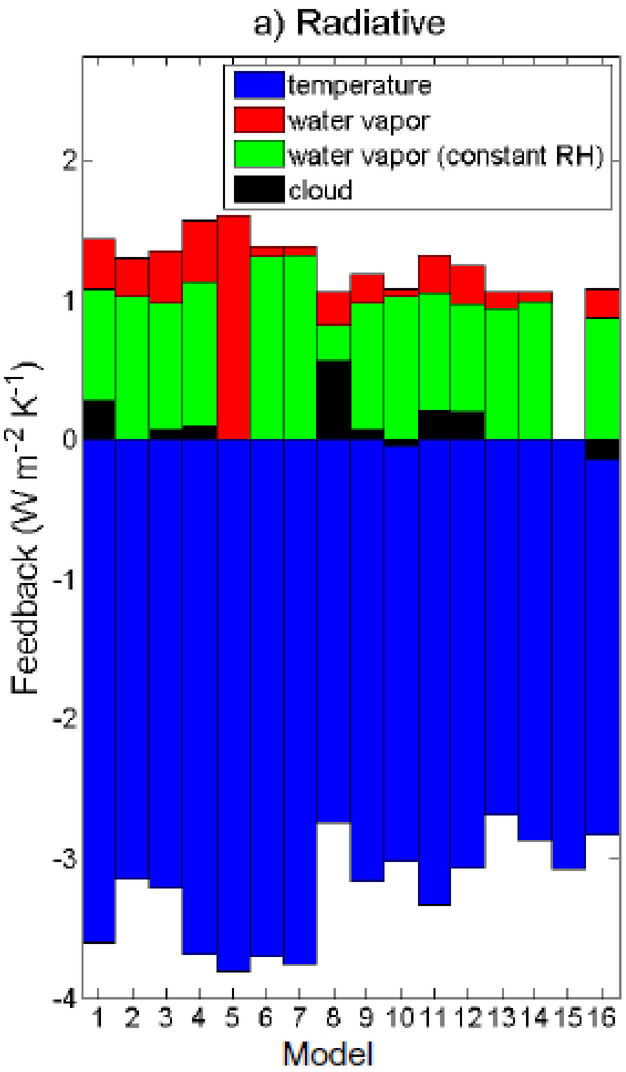
Lambert and Webb (2008), Figure 2

Previous work: Stephens and Ellis (2008)

- Framed the precipitation and atmospheric energy budget changes in terms of water vapor
  - $efficiency = \frac{precipitation\ change}{water\ vapor\ change} \sim R_a$
- Used an empirical formula for atmospheric radiation based on column water vapor
  - $R_{net,clr} \approx c_o + aW^b$

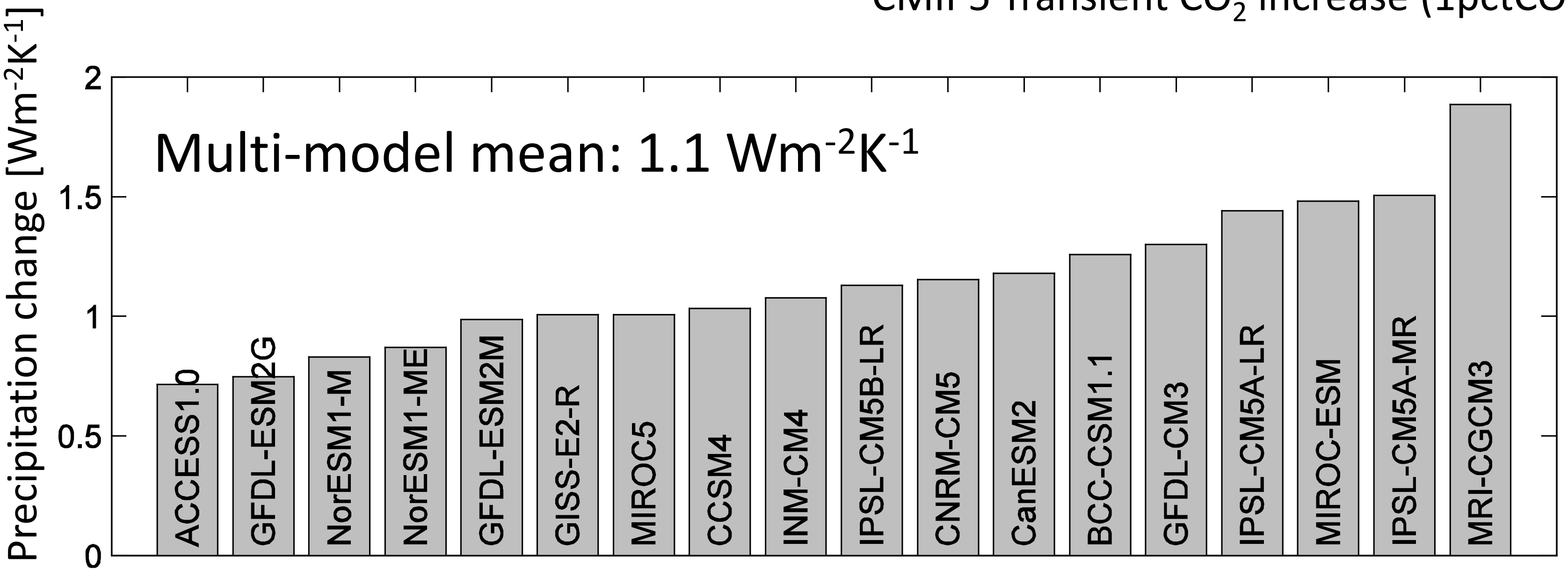
Previous work: Previdi (2010)

- Used feedback kernel diagnosis of change for AR4, A1b scenario (including aerosol change)



Previdi (2010), Figure 5

Precipitation as energy flux


CMIP5 Transient CO_2 increase (1pctCO2)