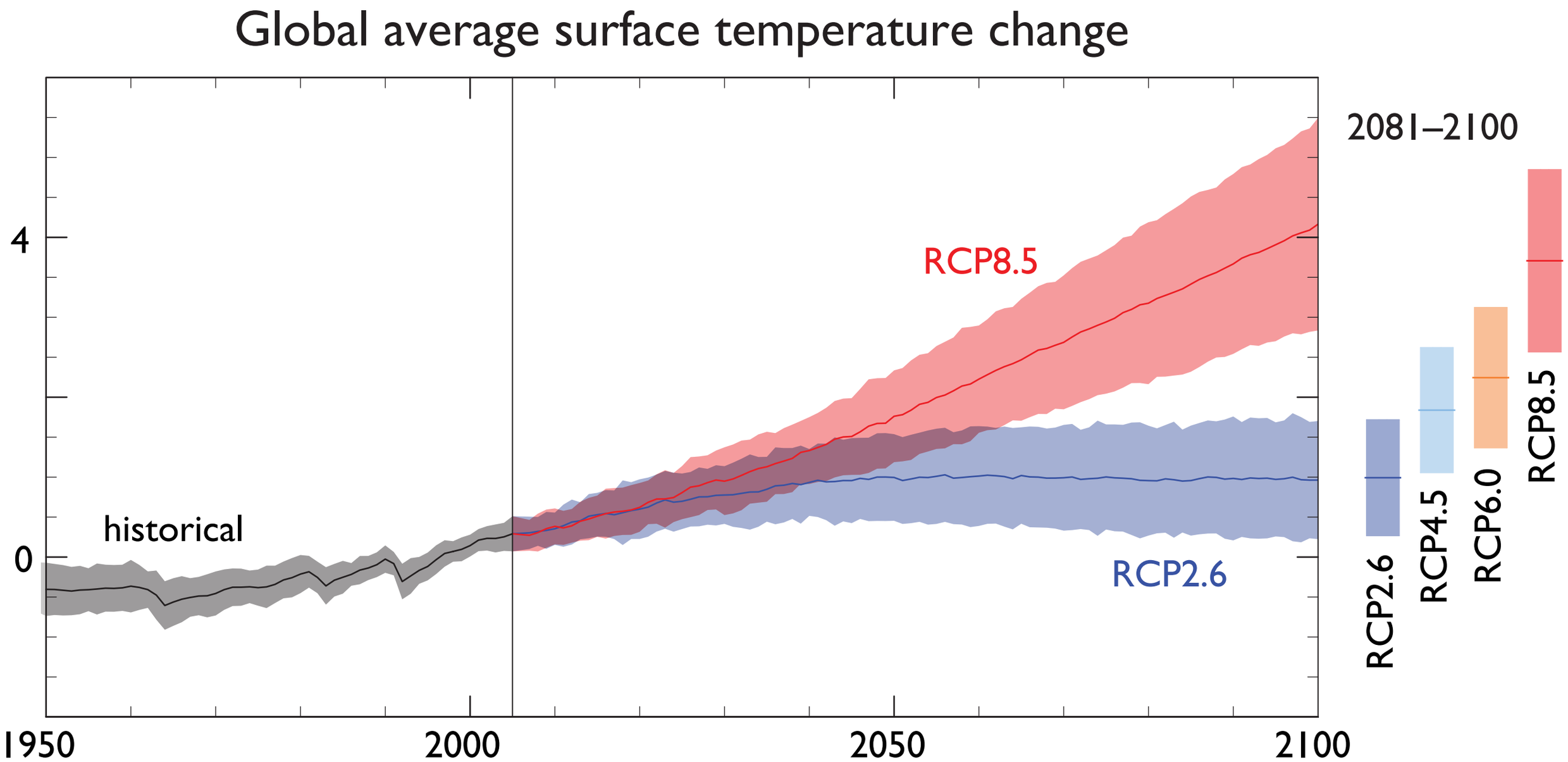
Making sense of radiative forcing

Robert Pincus
University of Colorado

Reading list:
Boucher et al. 2013 (IPCC AR5, Chapter 7)
Myhre et al. 2013 (IPCC AR5, Chapter 9)
Sherwood et al. 2015 (to appear in BAMS)

What drives the diversity in projections of climate change?



Adapted from IPCC, 2013 (SPM.7), doi:10.1017/CBO9781107415324.004

In the beginning…

… there was radiative equilibrium

$$N = (1 - a)S_0 - \epsilon\sigma T^4 = 0$$

Then Man appeared introduced a forcing that disturbed the equilibrium

$$N = F$$

and the planet responded

$$N = F - \Delta R$$

Four points about $N = F - \Delta R$

Forcing is a *change:* a difference between two states

Response depends only on forcing: common currency

Imbalance and forcing are fundamentally radiative quantities; response depends on "the climate system"

Imbalance in the absence of response is "instantaneous radiative forcing." We'll have to compute this

Forcing and feedback

For small perturbations we assume the radiative response is linear in ΔT

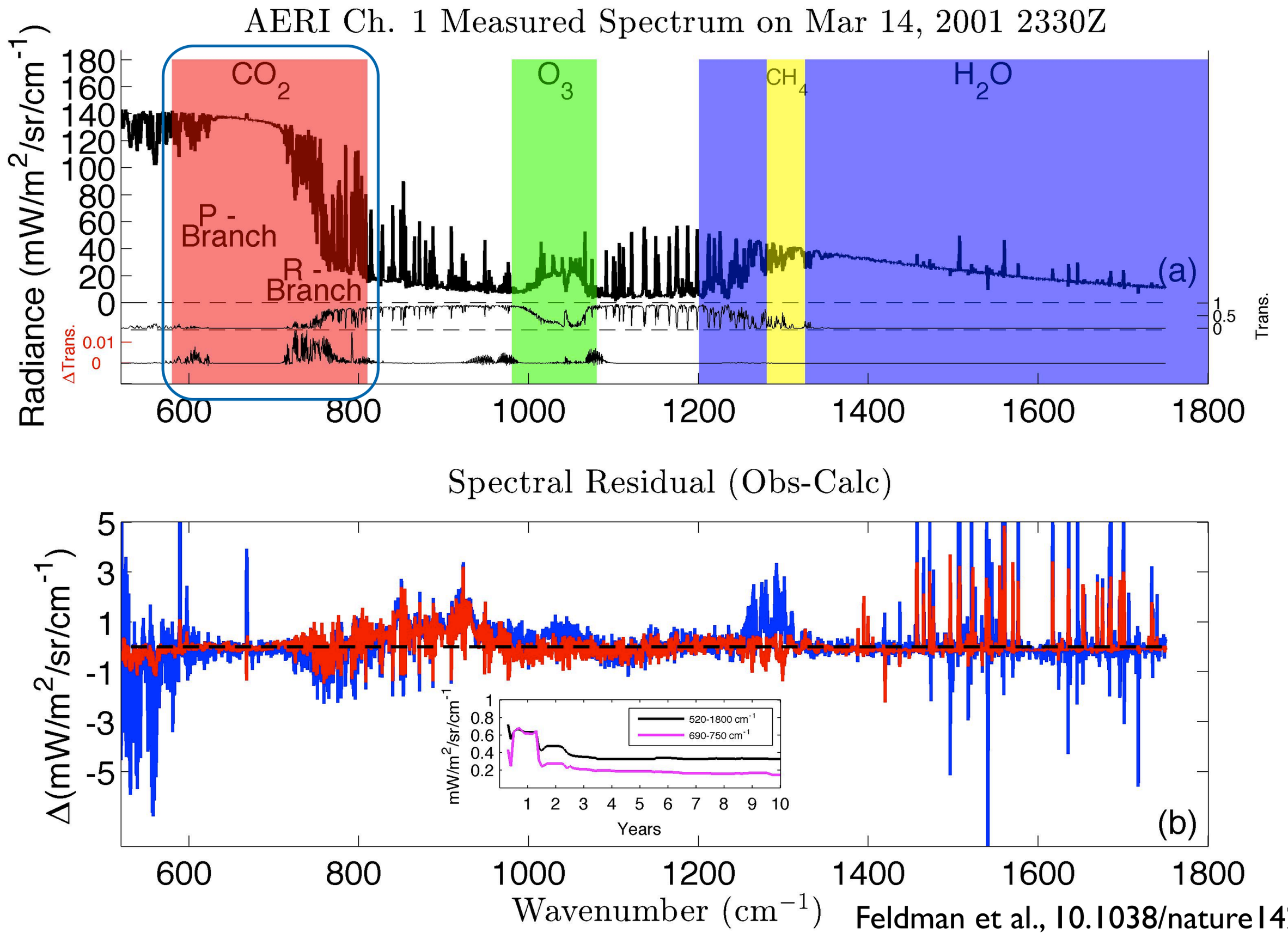
$$N = F - \alpha \Delta T$$

where the climate feedback is the sum of all feedbacks

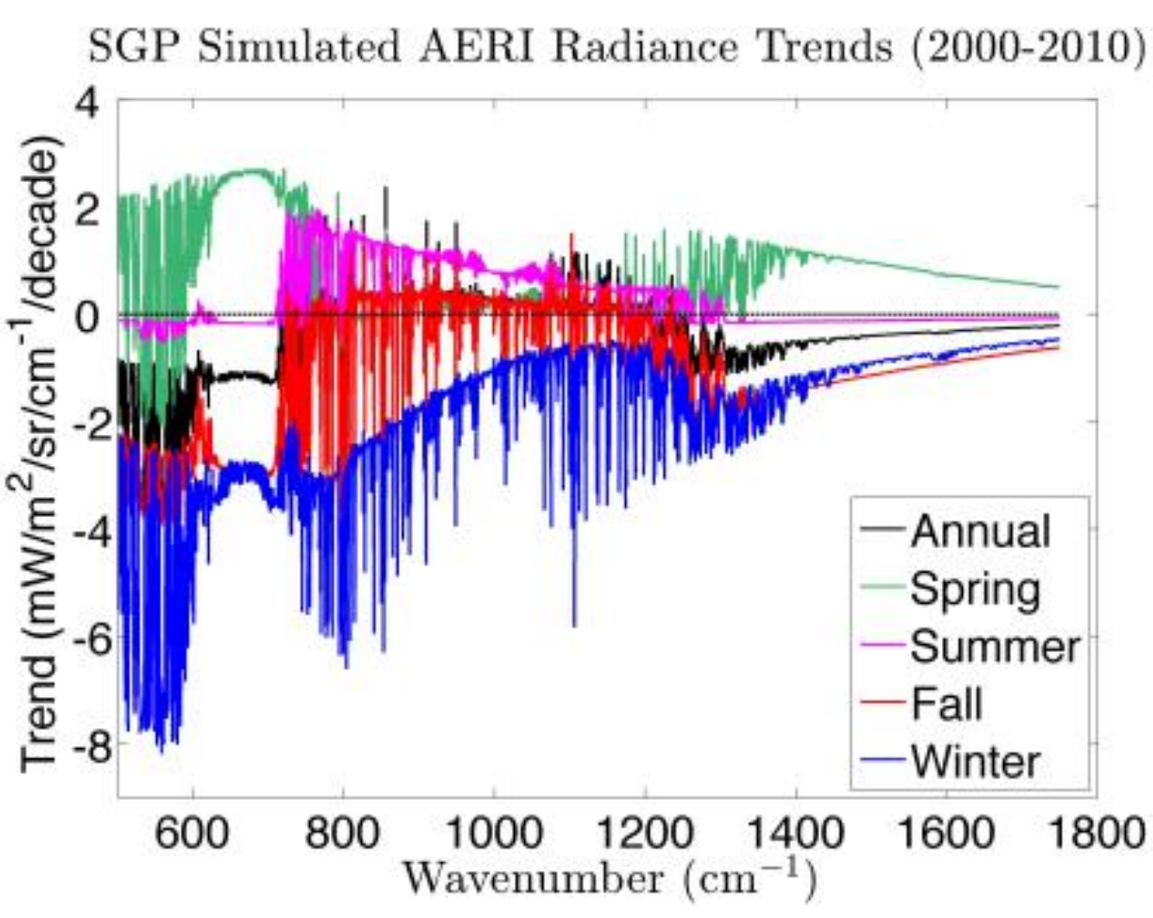
$$\alpha = (\frac{\partial R}{\partial T} + \sum_i \frac{\partial R}{\partial X_i} \frac{\partial X_i}{\partial T})$$

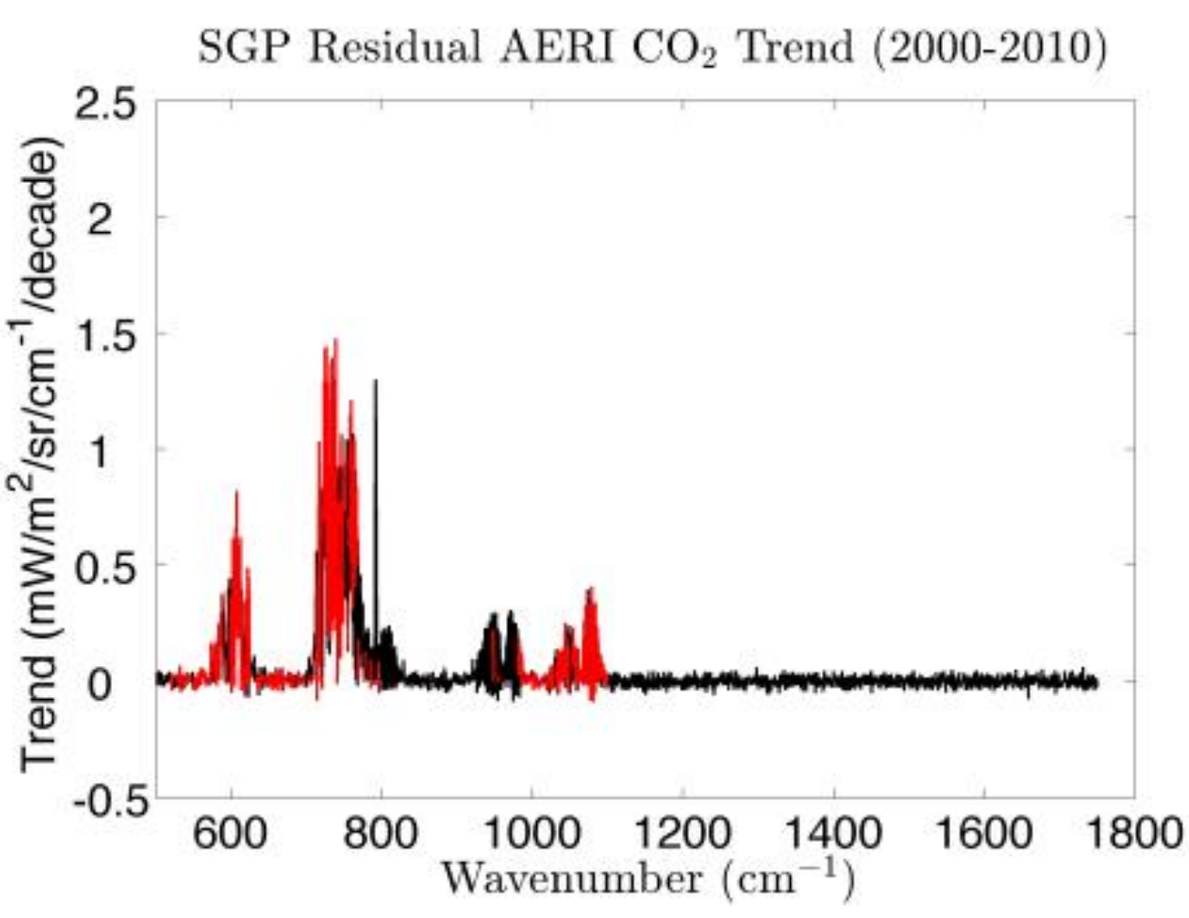
where the X_i are state variables that control planetary albedo and emissivity

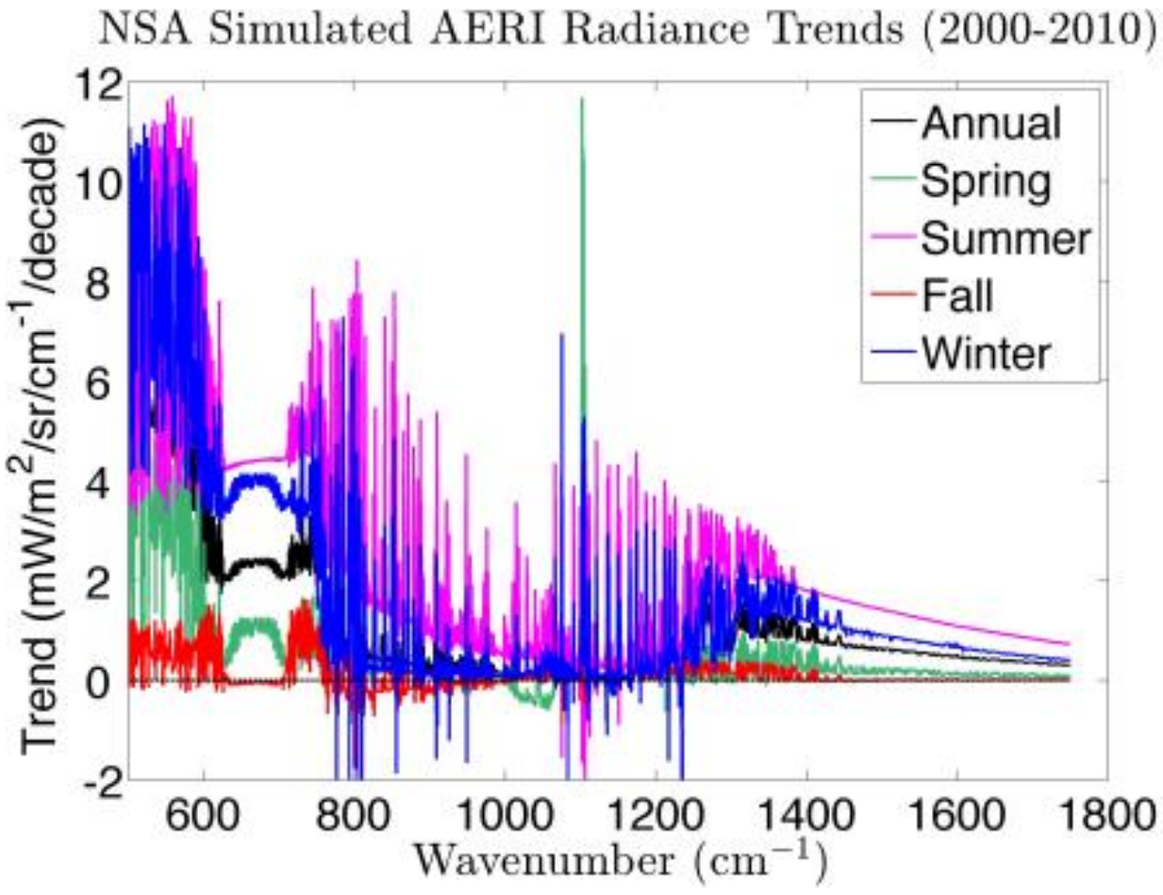
How hard can this be? We understand radiation really well…

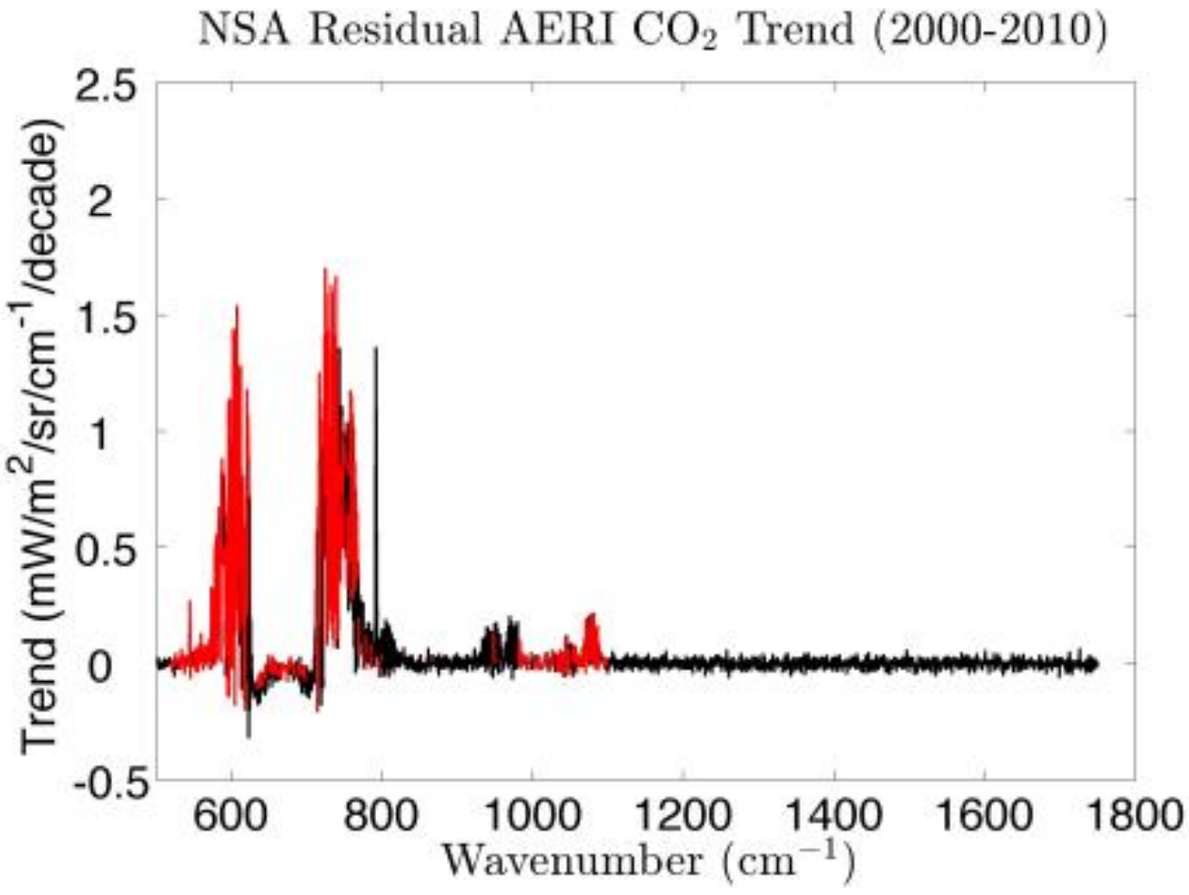


Feldman et al., 10.1038/nature14240







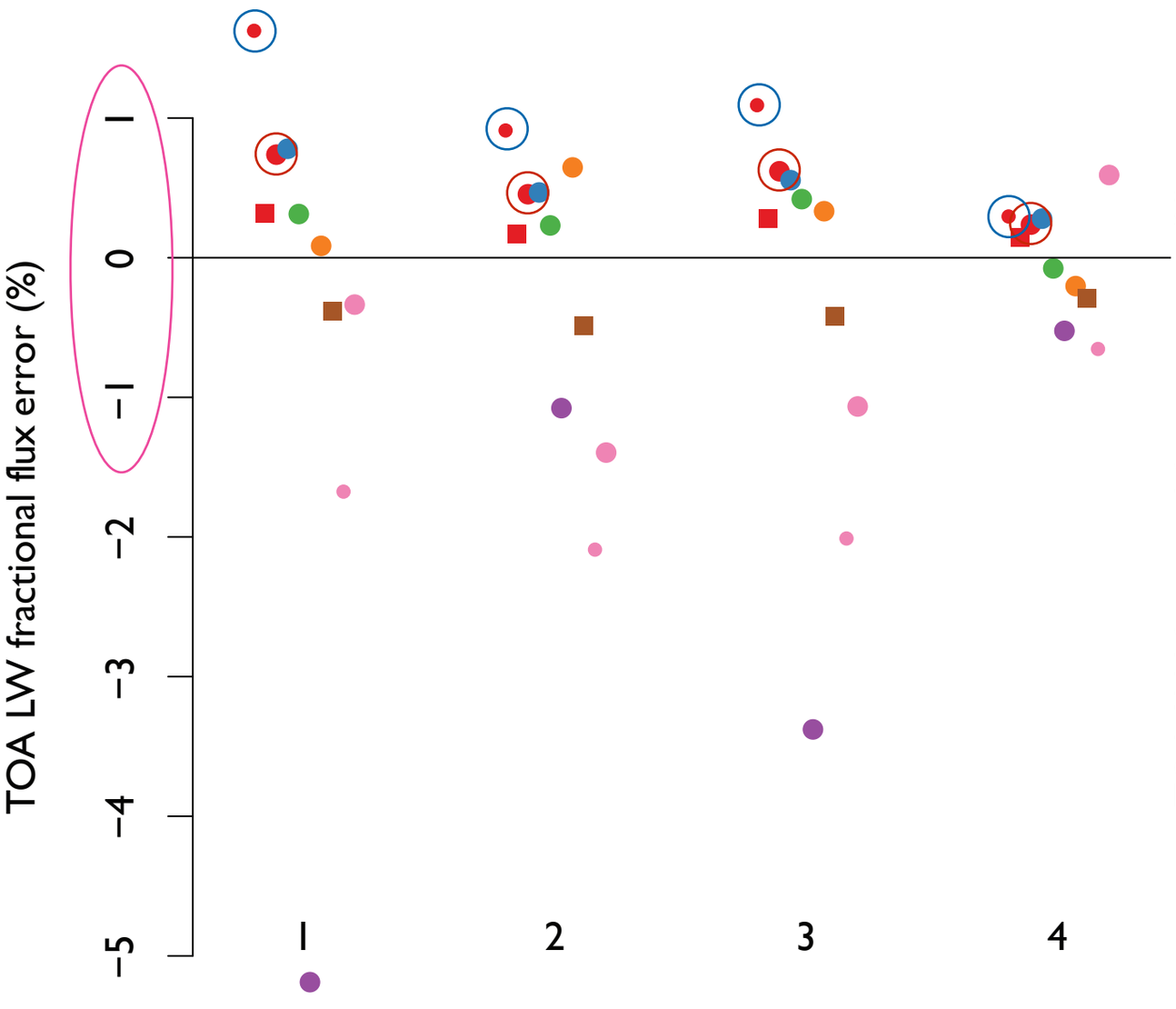


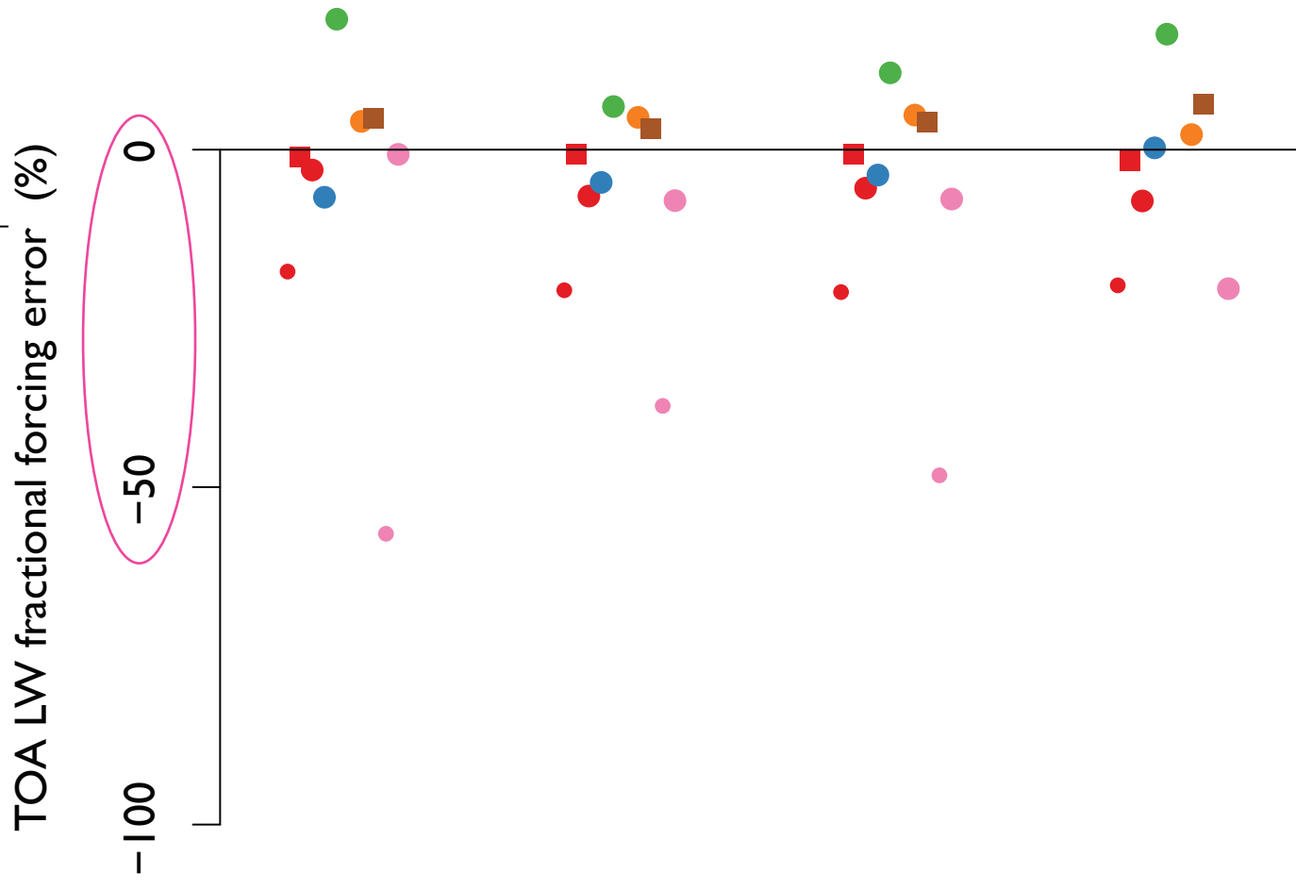
Feldman et al., 10.1038/nature14240

Composition changes don't uniquely determine model forcing (i)

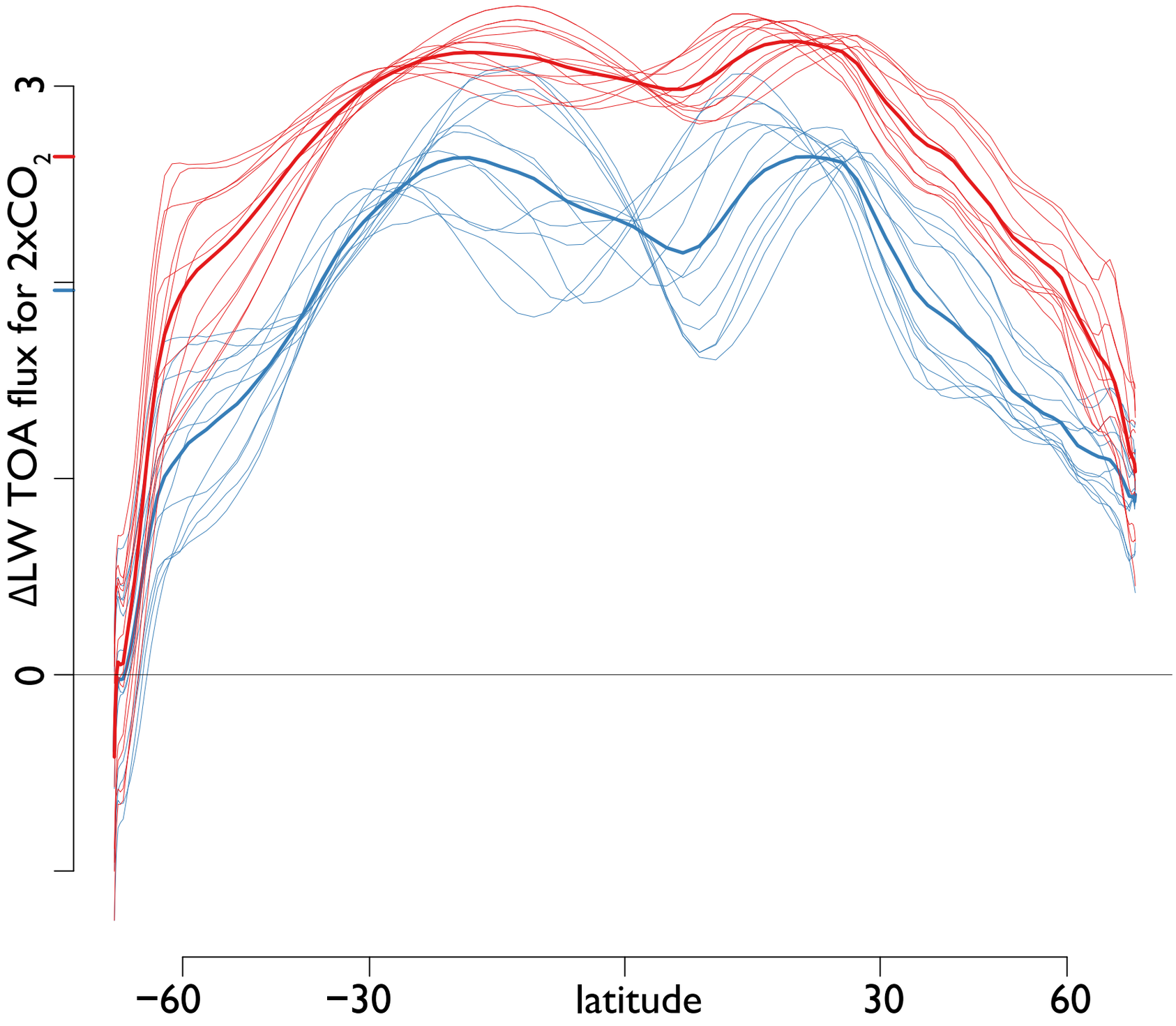
Radiation parameterizations used in climate models show a range of skills, especially when far from present-day conditions (think 4xCO_2)

Tangent: Skill for absorption is much worse than flux



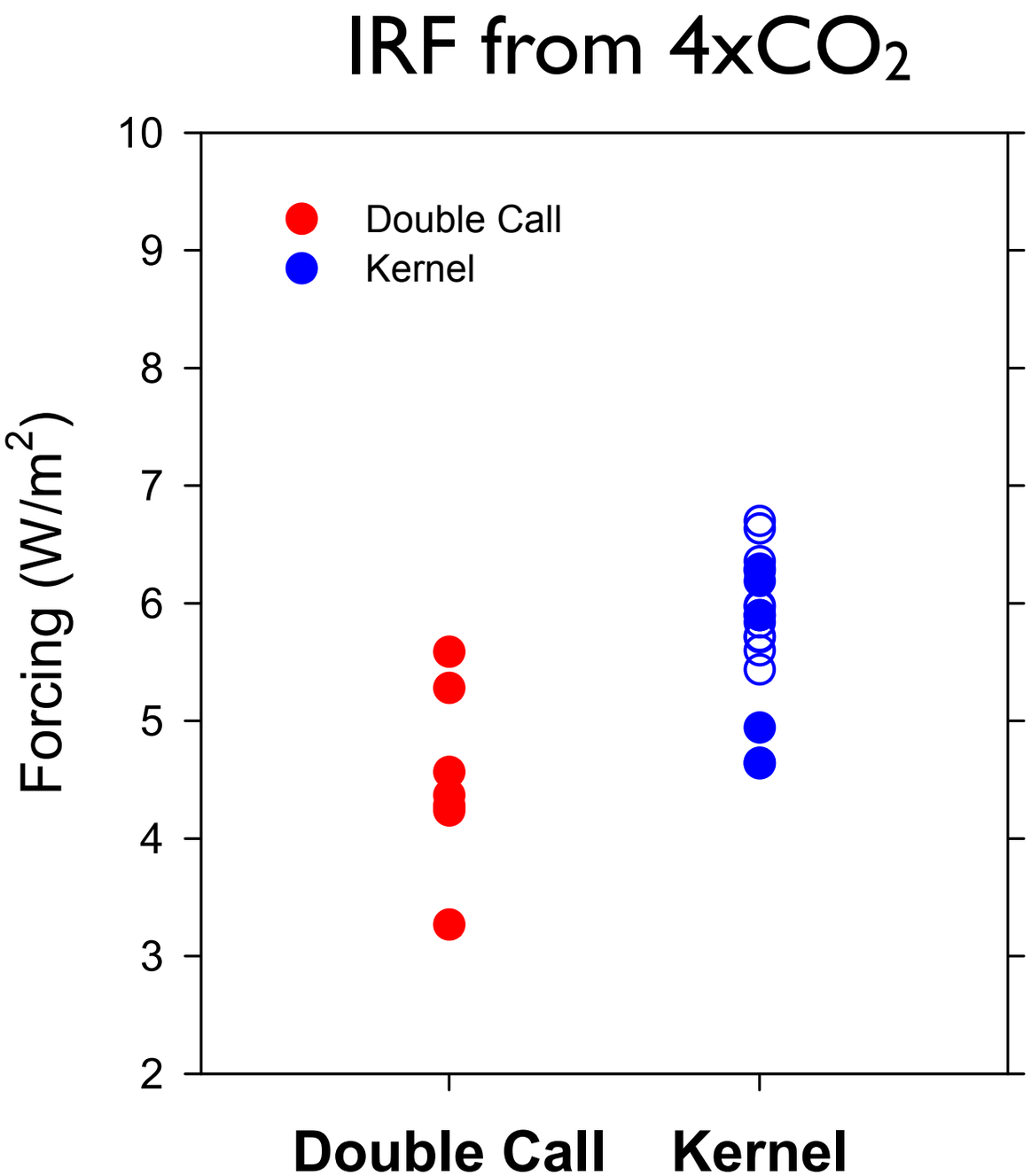


Composition changes don't uniquely determine model forcing (ii)

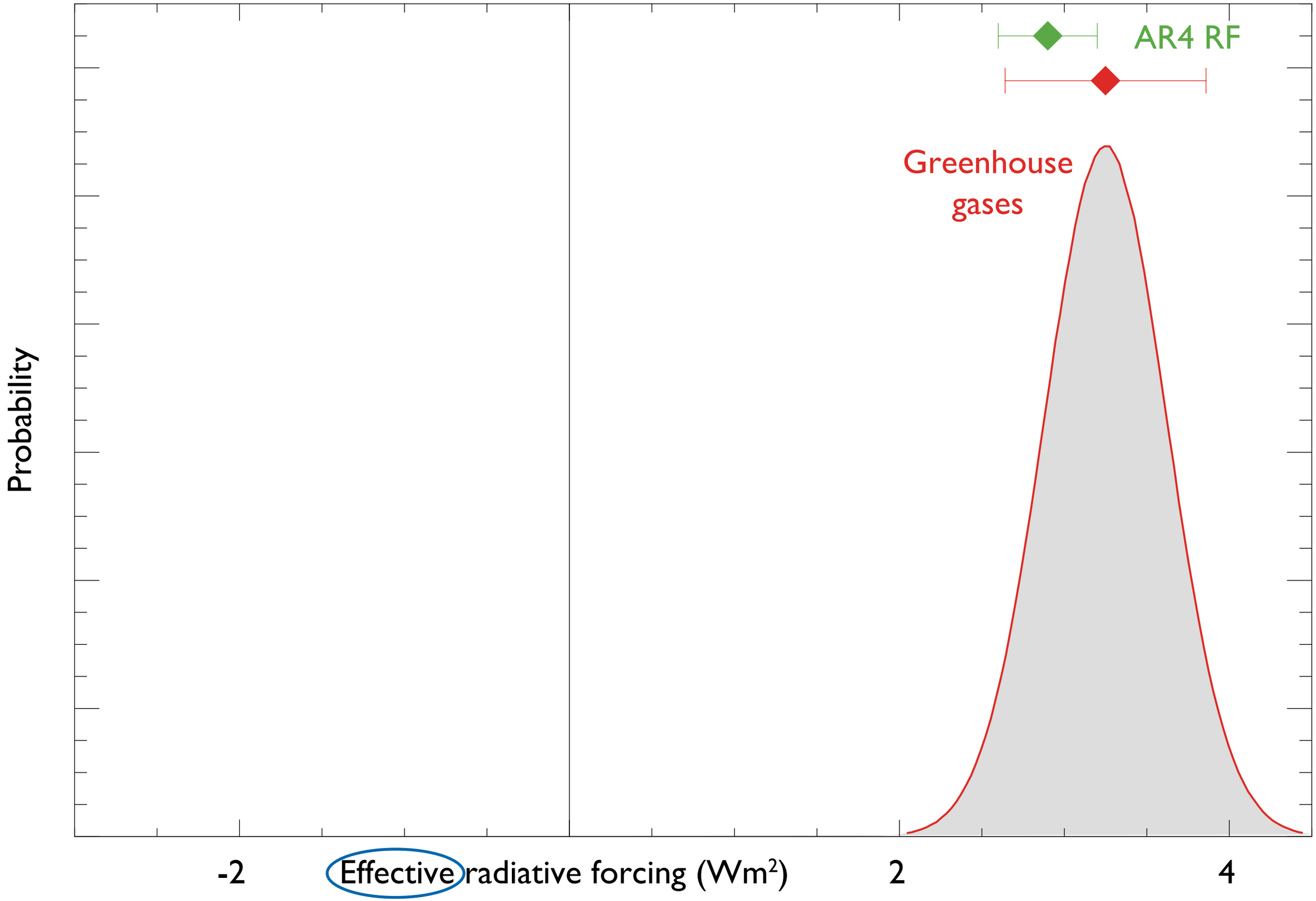


After Block and Mauritsen 2013, doi:10.1002/jame.20041

Still, the diversity among climate models is kind of shocking…

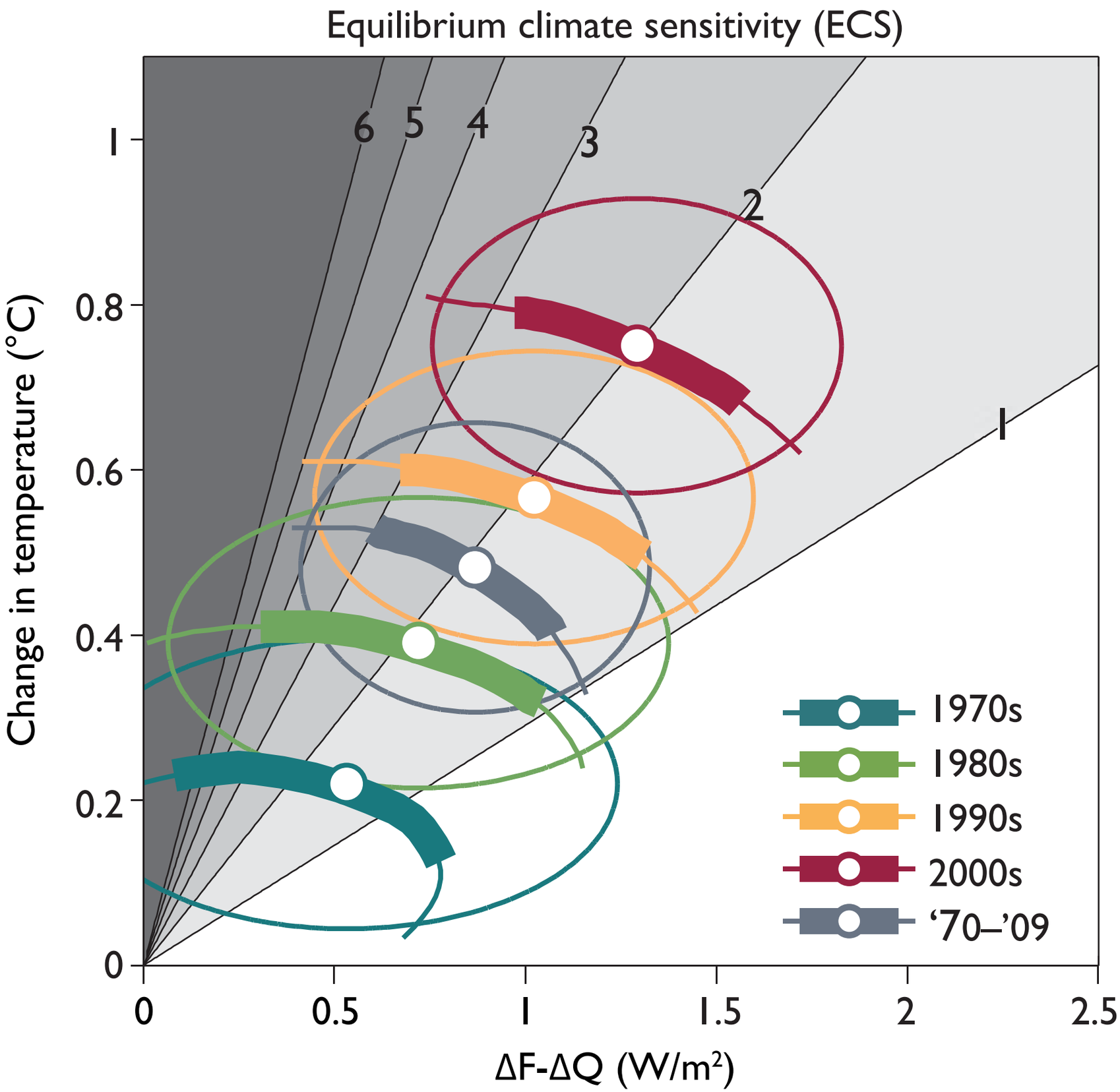


Choi and Soden, pers. comm.



Adapted from Myhre et al., 2013 (8.16), doi:10.1017/ CBO9781107415324.018

Estimating sensitivity from forcing and response



Otto et al., 2013, doi:10.1038/ngeo1836

The limits of a purely radiative view

The goal of radiative forcing is to make a prediction about climate response, and it's been known for decades that instantaneous flux changes at the top of atmosphere are not good predictors of surface warming.

> "The simplest useful definition of radiative forcing is the instantaneous flux change at the tropopause" (Hansen et al. 1997, doi:10.1029/96JD03436)

We look at the tropopause because surface temperature is tied to tropospheric temperature, while stratosphere strongly modulates top-of-atmosphere fluxes

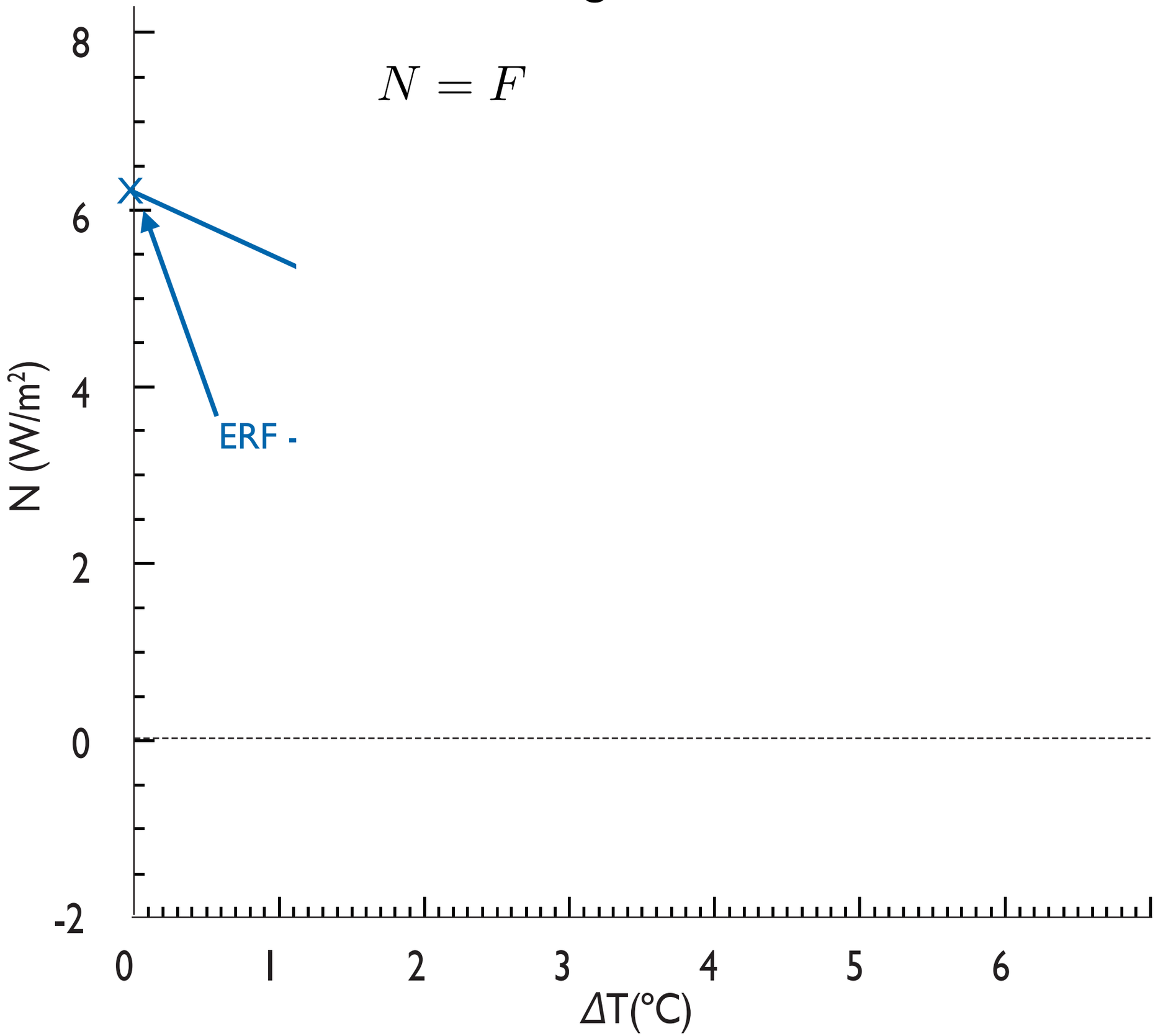
> "An improved measure of radiative forcing is obtained by allowing the stratospheric temperature to adjust … to a radiative equilibrium profile" (*ibid*)

"Stratospheric adjustment" is necessary because the stratosphere reaches a new radiative equilibrium in a matter of months

Allowing for stratospheric adjustment implies that radiative forcing is no longer strictly a problem in radiation. How else might we compute forcing?

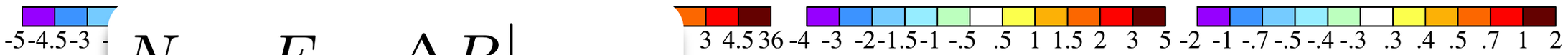
Response to an instantaneous forcing

$$N = F$$



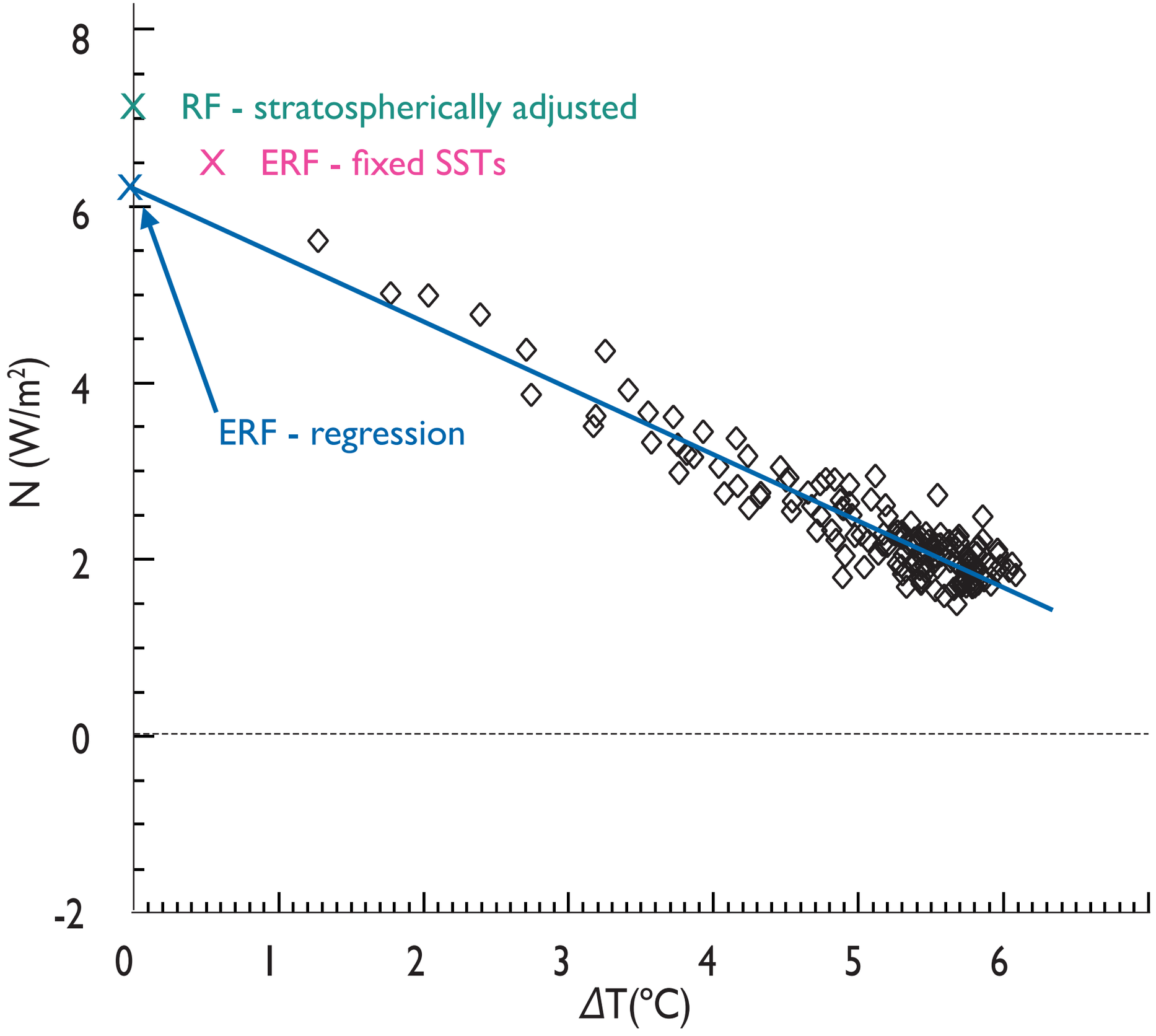
Adapted from Boucher et al 2013 (7.2), doi:10.1017/CBO9781107415324.016

	"Adjusted" forcing (W/m^2)	Fixed-SST forcing (W/m^2)	ΔT_s (°C)	$\Delta T_s / \langle F_s \rangle$
All GHGs	2.40	2.55	1.21	.48
$2xCO_2$	4.12	4.11	1.96	.48
$2xCH_4$	1.15	1.20	.59	.49
$6xN_2C$	3.47	3.62	1.67	.46
4xCFCs	1.04	1.41	.64	.45



$$N = F - \Delta R\big|_{\Delta R=0}$$

Hansen et al., 2005, doi:10.1029/2005JD005776



Adapted from Boucher et al 2013 (7.2), doi:10.1017/CBO9781107415324.016

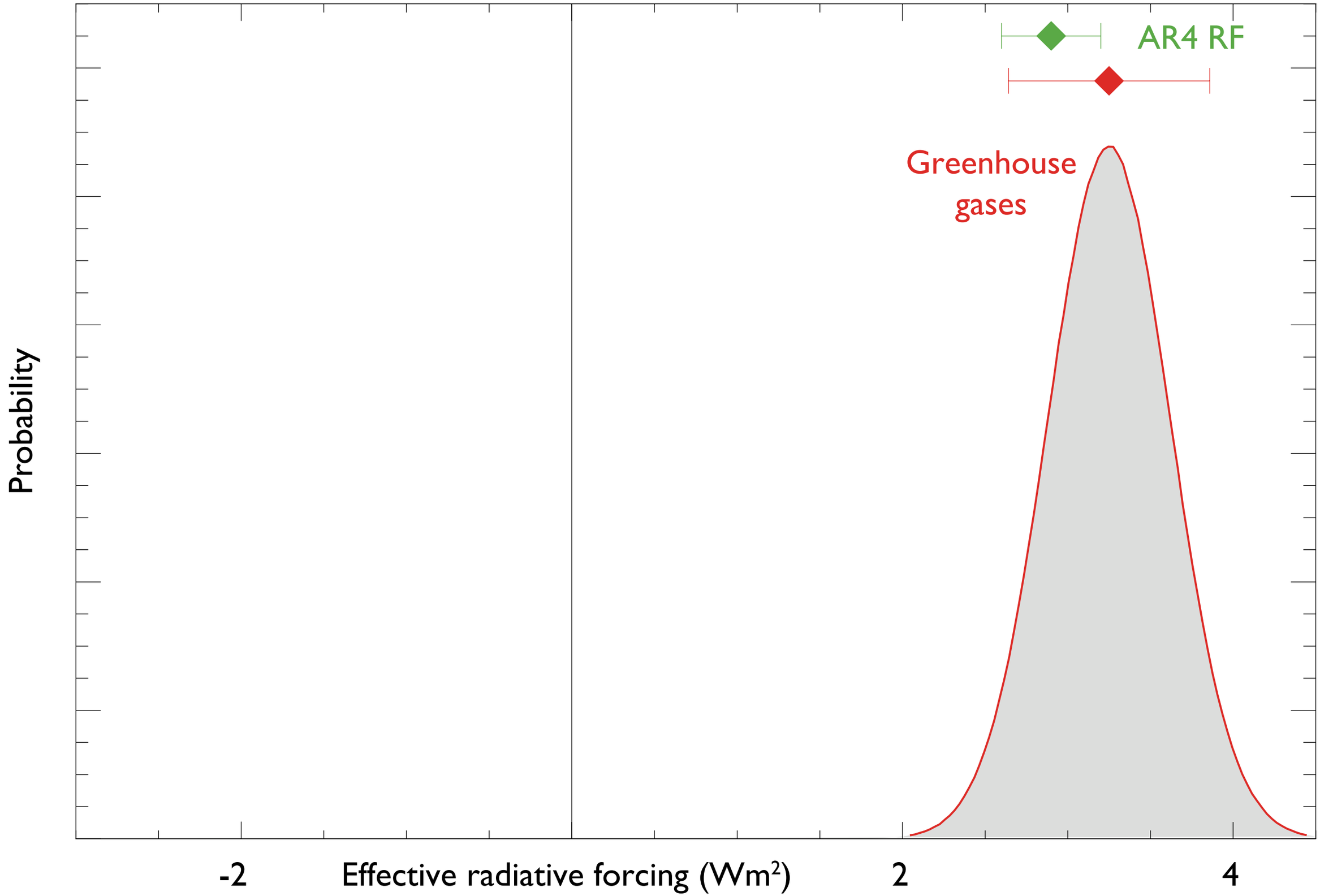
The limits of fungibility

Stratospheric adjustment is the tip of the iceberg

Different radiative perturbations can easily have the *same forcing* but very different, say, spatial distributions. These differences can induce *different responses* that impact mean temperature change.

Responses that don't scale (global-mean surface) temperature response are called *adjustments*

Adjustments are lumped in with forcing even though they are a response



Adapted from Myhre et al., 2013 (8.16), doi:10.1017/ CBO9781107415324.018

The nature of adjustments

Adjustments can change any aspect of the climate system, especially circulation, precipitation…

A component of the climate can have feedbacks and/or adjustments

Most (all?) responses to aerosol changes are adjustments

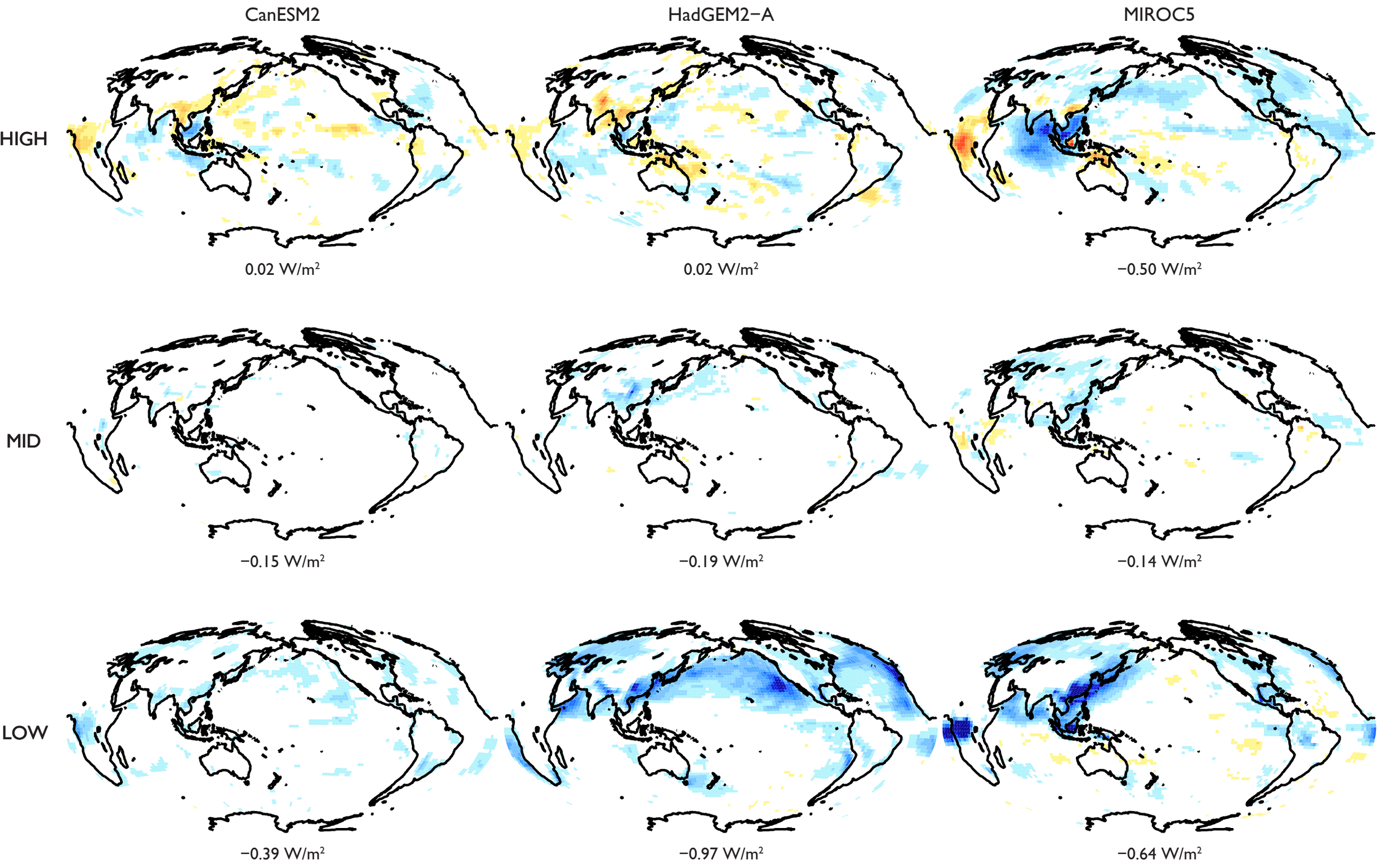
Roughly speaking, adjustments add directly to feedbacks

Most adjustments are quick but time-scale separation is a convenience

Global
Ocean
Land
AOGCM
AMIP
TAMIP
T (°C)
1
0
SW
LW
CRE (W/m²)
3
-3
Latent heat
Sensible heat
Precip
Precip (mm/d)
0.2
-0.2
Flux (W/m²)
6
-8
1
Day
10

Adapted from Kamae and Watanabe 2013, doi:10.1007/s00382-012-1555-1

Adjustments vary among models



Zelinka et al. 2014, doi:10.1002/2014JD021710

Consequences (i)

"Effective radiative forcing" = instantaneous radiative forcing + adjustments

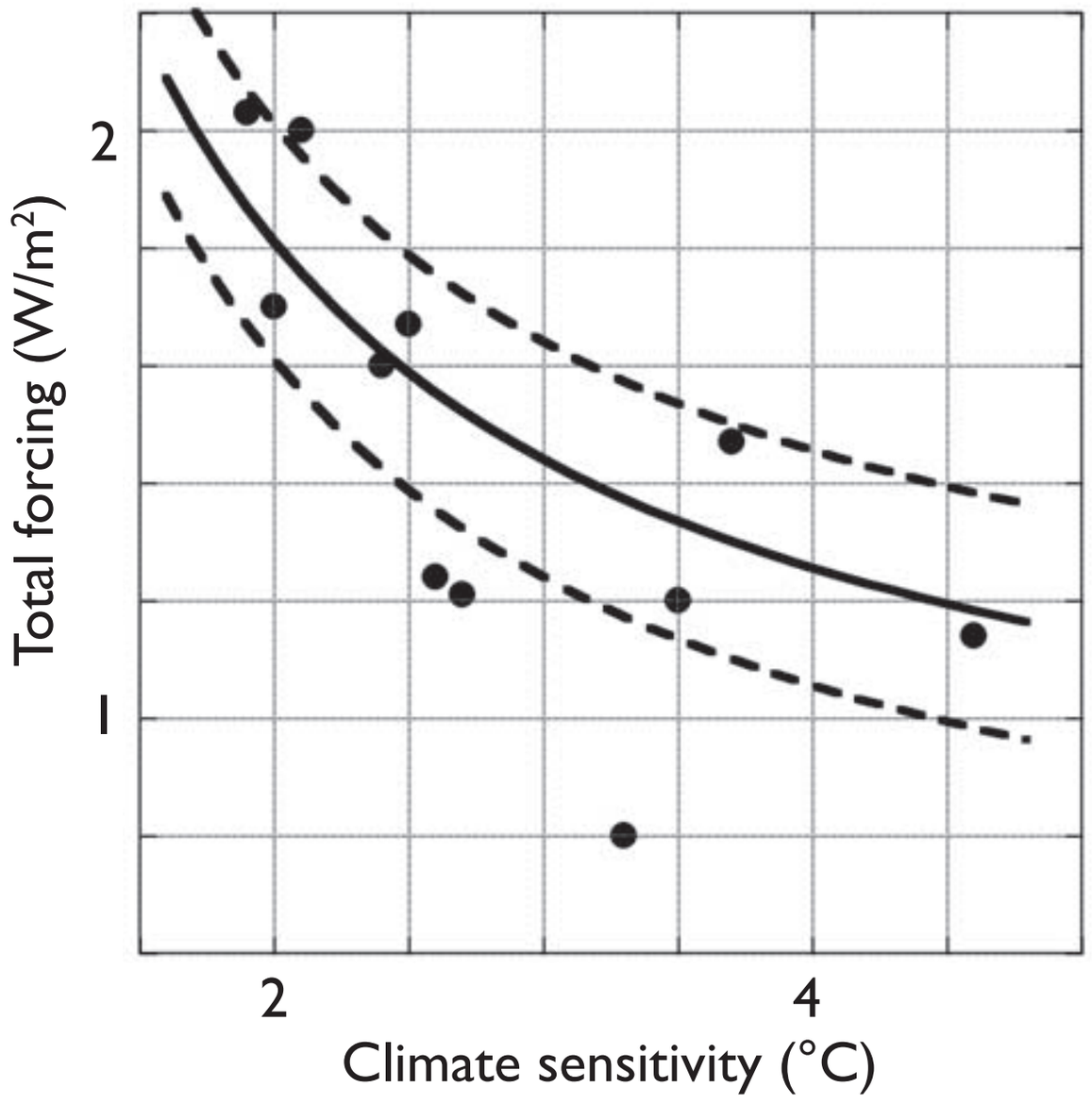
Adjustments are why geoengineering strategies leave the planet changed even if temperature is unchanged

Adjustments add model-specific diversity

> "…climate sensitivity is the product of two quantities, the radiative forcing of a doubling of CO_2 and a climate sensitivity parameter. It has been assumed that the former is known exactly. In fact it is not, especially when adjustments are considered as part of the forcing."
> Sherwood et al. 2015 (doi:10.1175/BAMS-D-13-00167.1)

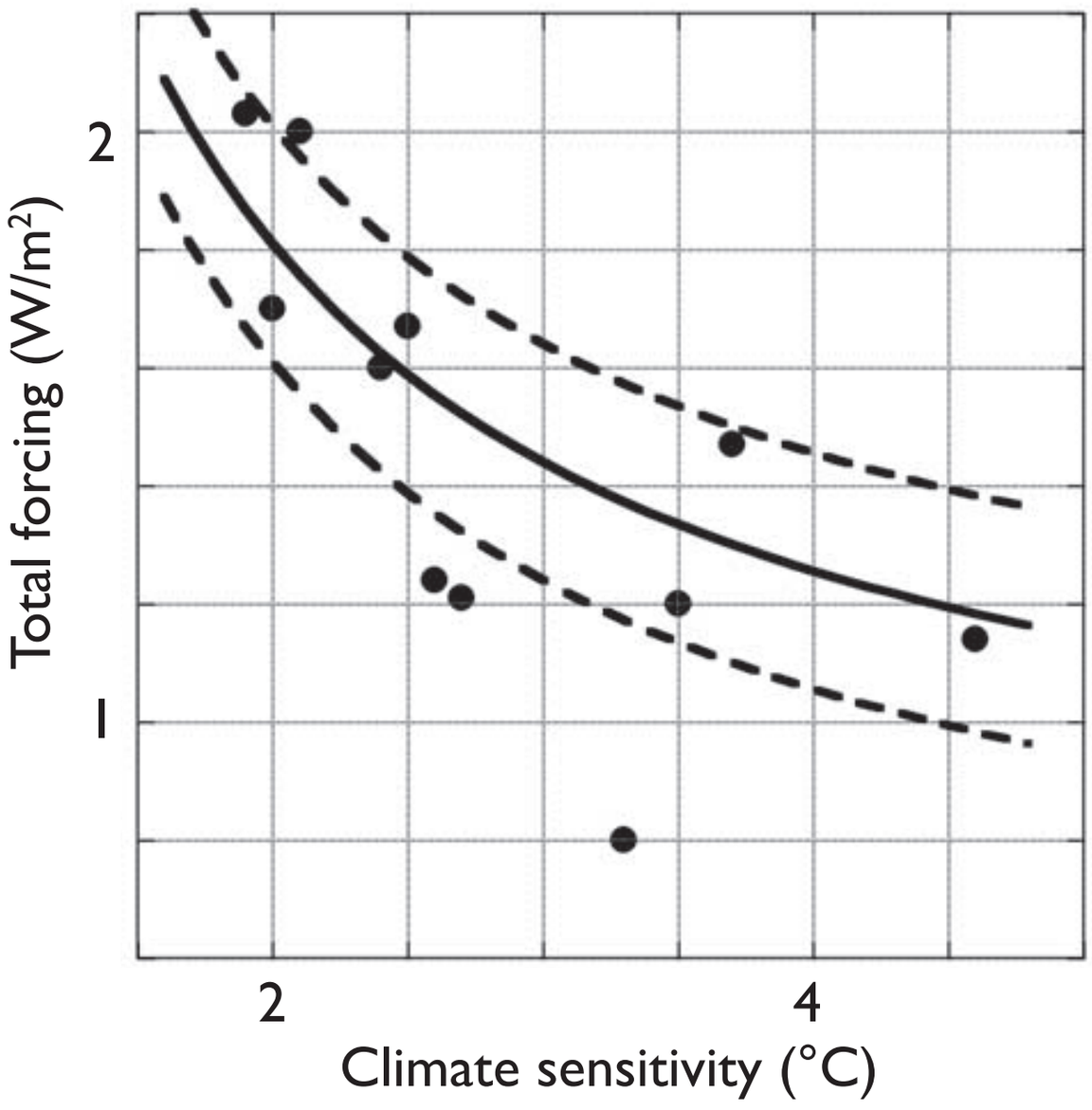
Consequences (ii)

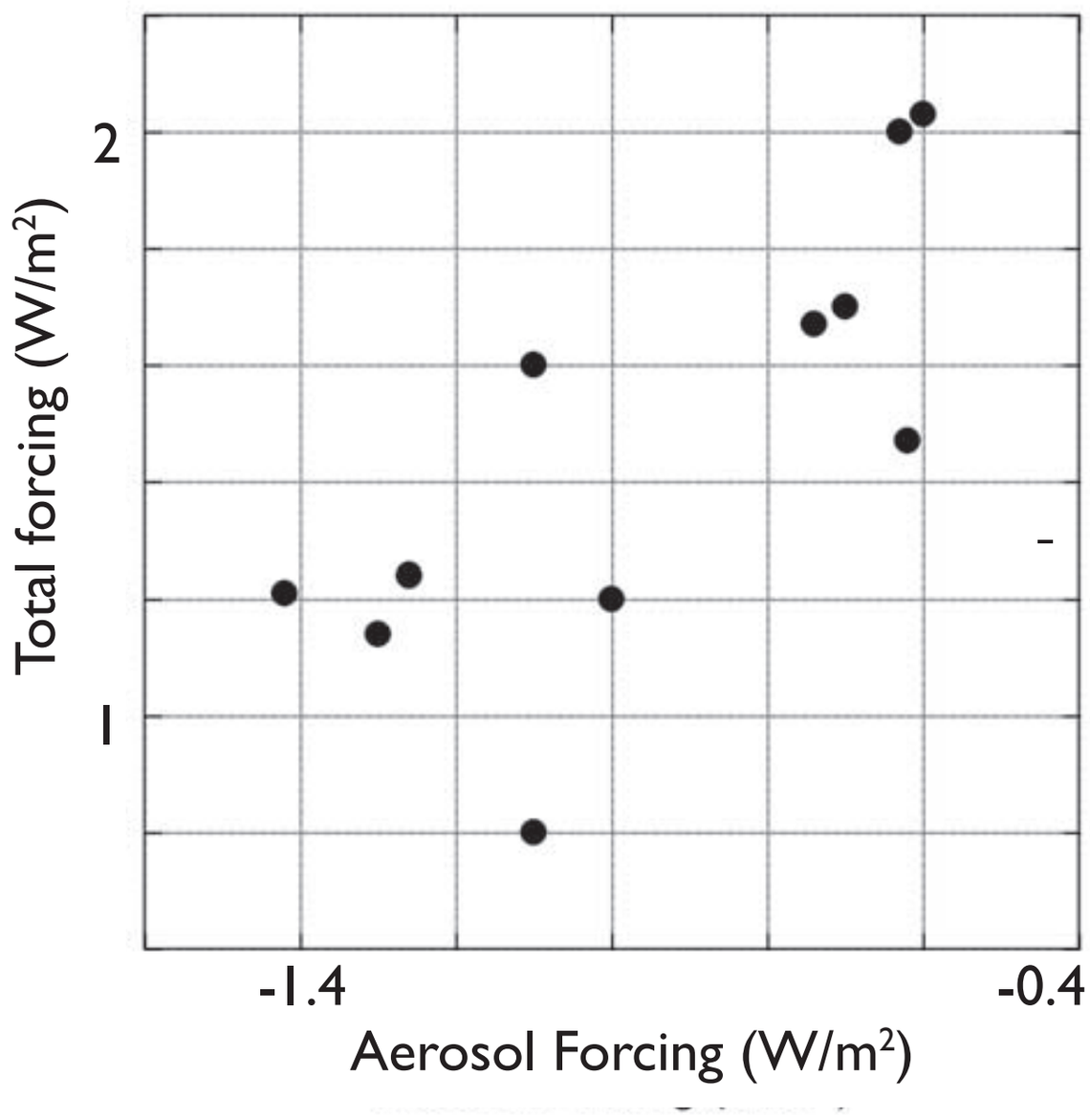
If historical forcing+adjustments varies among models, but all roughly reproduce the historical temperature change…



Kiehl 2007, doi:10.1029/2007GL031383

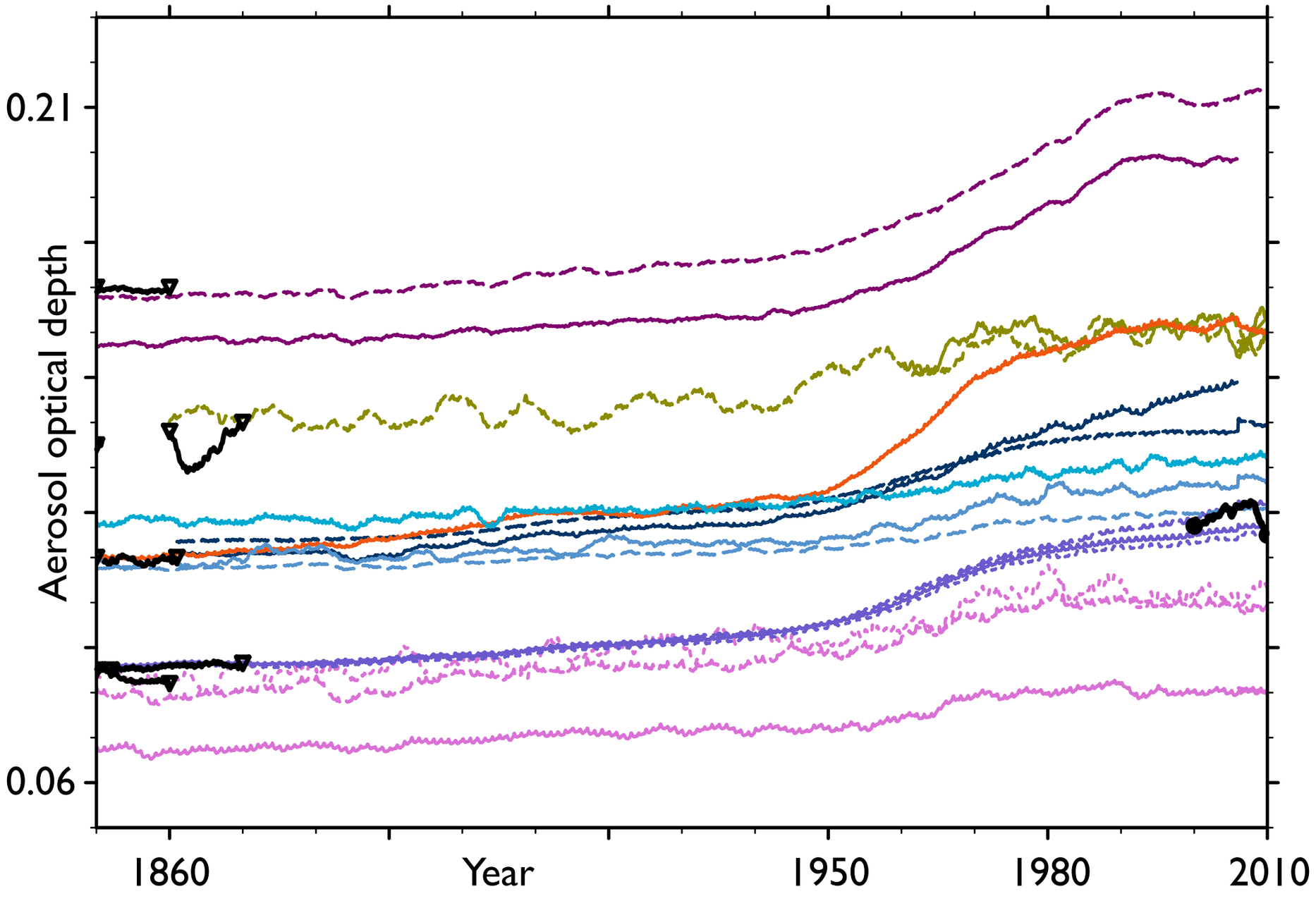
Diversity in historical forcing+adjustments is dominated by aerosols
(unspecified in CMIP)



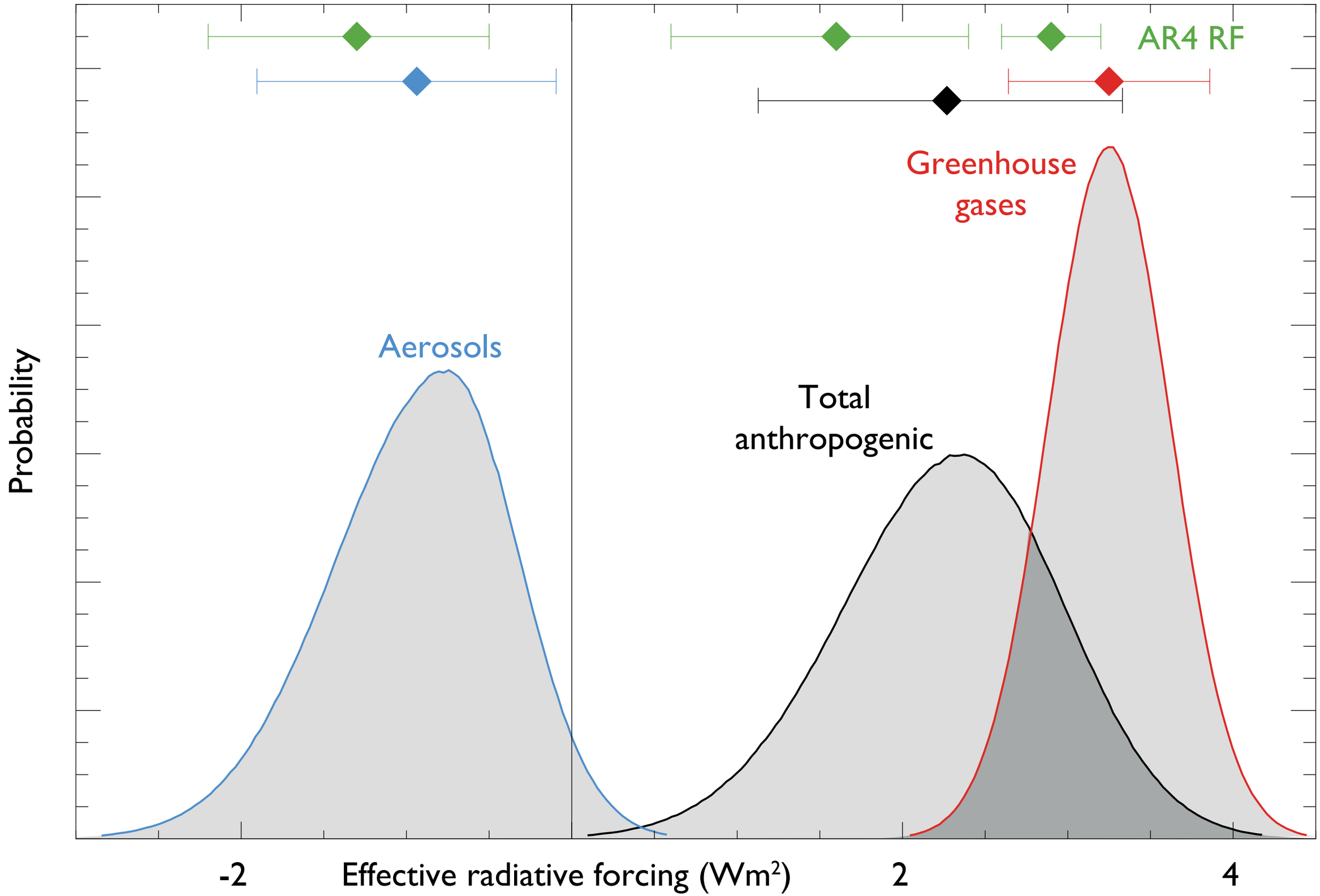


Kiehl 2007, doi:10.1029/2007GL031383

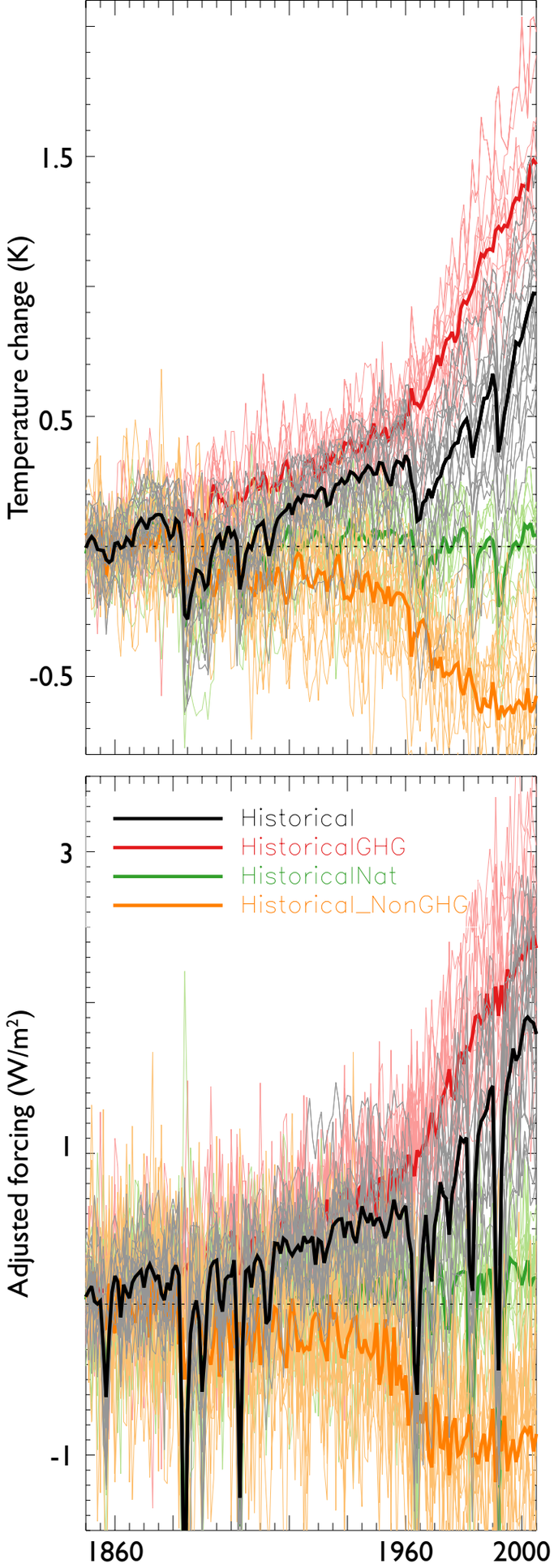
The situation is unimproved in recent generations of models



Shindell et al. 2013, doi:10.5194/acp-13-2939-2013



Adapted from Myhre et al., 2013 (8.16), doi:10.1017/ CBO9781107415324.018

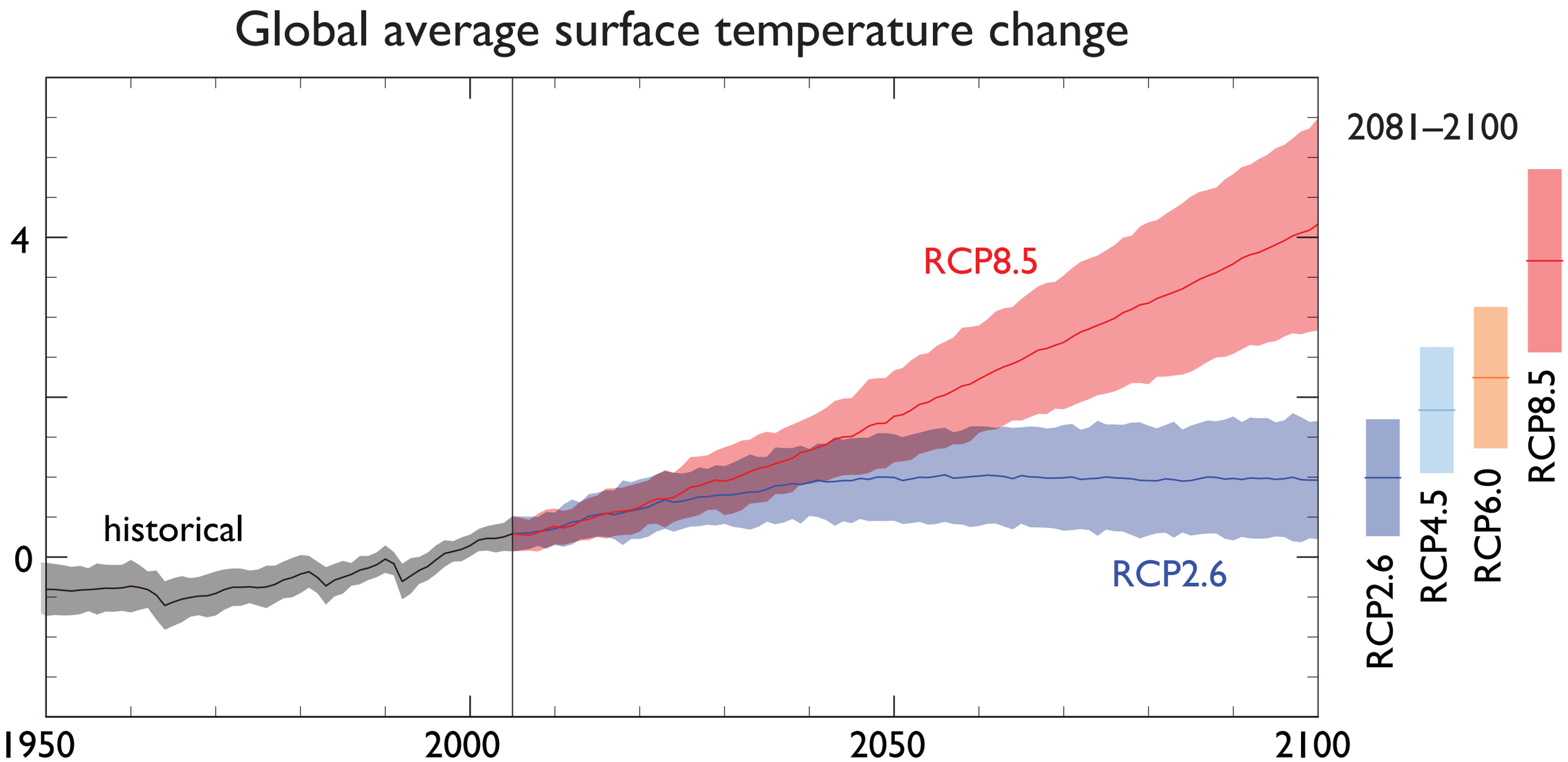


"the intermodel spread in the global surface temperature change across [CMIP5] historical simulations [is] primarily driven by differences in their present-day forcings" (Andrews 2014, doi:10.1175/JCLI-D-13-00336.1)

Because we require models to reproduce the observed temperature change, sensitivity and forcing are inversely related in the CMIP ensemble. Indeed, some amount of the diversity in sensitivity is required just to account for diversity in model-specific forcing over the historical record.

Forster et al. 2013 doi:10.1002/jgrd.50174

What drives the diversity in projections of climate change?



Adapted from IPCC, 2013 (SPM.7), doi:10.1017/CBO9781107415324.004

Radiative forcing has less to do with radiation then with the climate system in a forcing-feedback (or forcing-adjustment-feedback) paradigm

> The power of radiative forcing is that it makes changes to the climate system interchangeable; the weakness is that it sweeps important differences under the rug

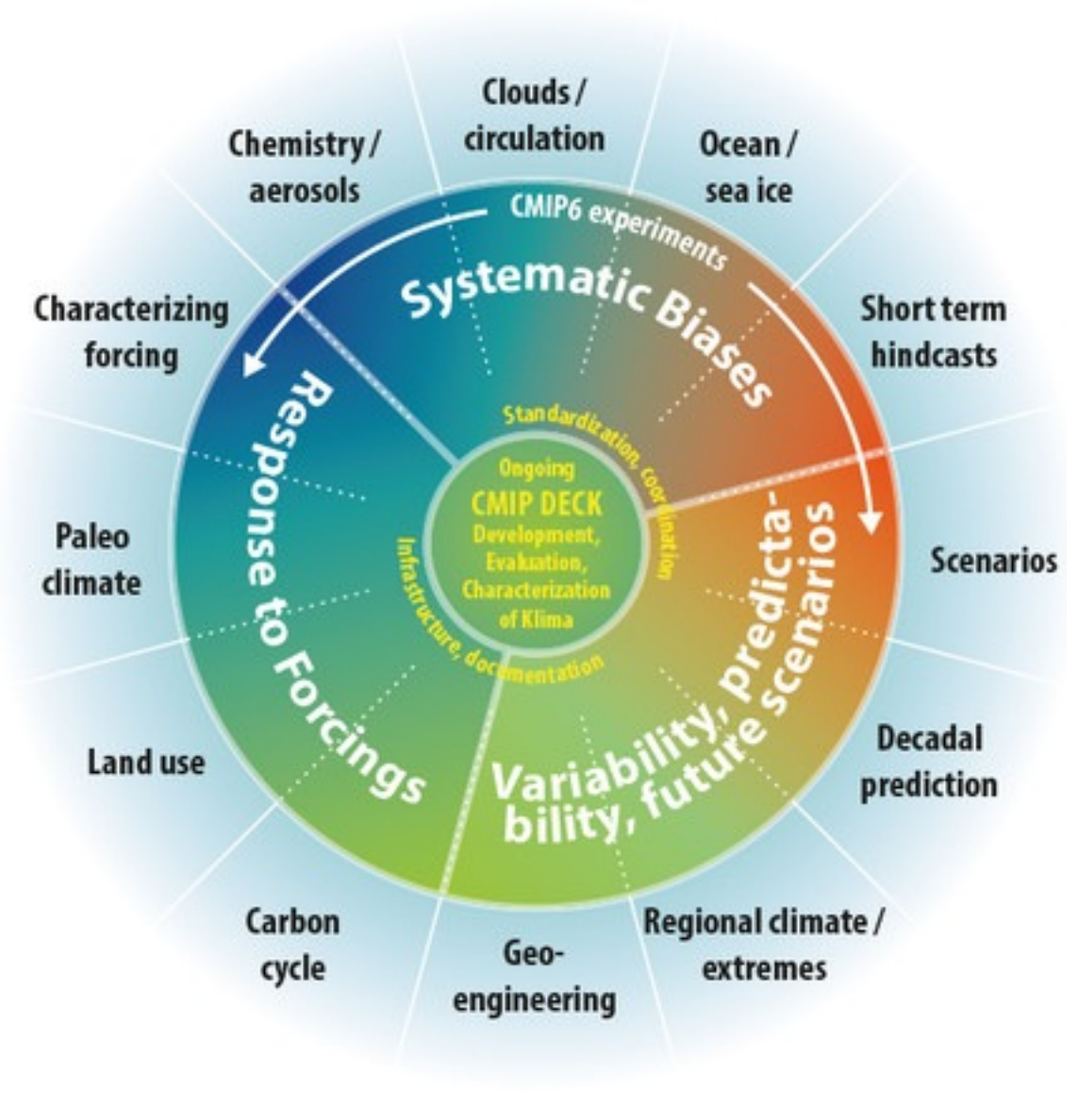
Adjustments help clarify relationships between forcing and response, especially for transient responses

Understanding the forcing to which each of our models is subject is non-trivial

Doesn't every question need a MIP?

As one of the spokes of CMIP6 we've proposed a Radiative Forcing MIP

Instantaneous forcing in clear skies (gases, aerosols)
Effective radiative forcing and adjustments
Simplified, specified forcing by aerosols



Meehl et al 2014, doi:10.1002/2014EO090001