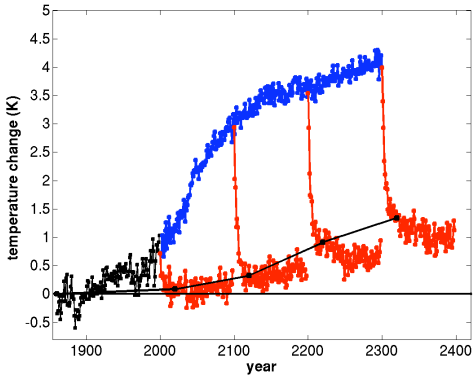
Fast and slow climate responses

Isaac Held
Wallace Symposium, Sept. 2010



Importance of Ocean Heat Uptake Efficacy to Transient Climate Change

Winton, Takahashi, Held, J. Clim, 2010

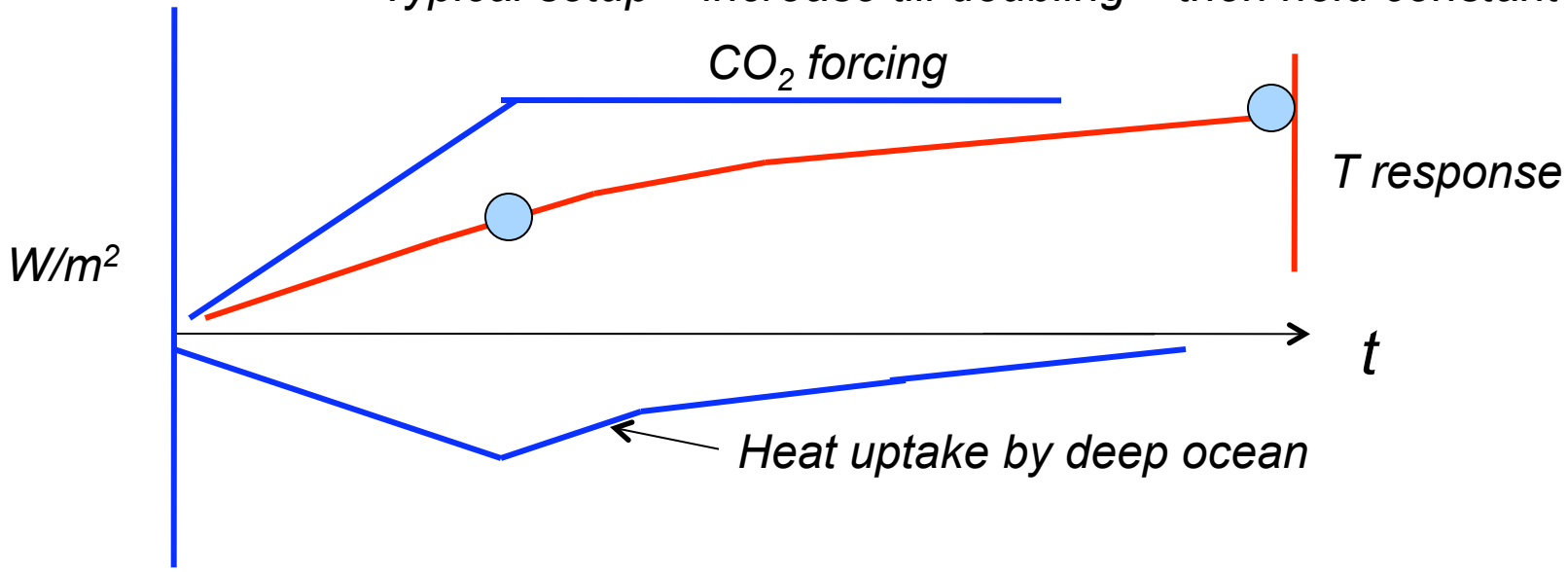
Probing the fast and slow components of global warming by returning abruptly to pre-industrial forcing

Held, Winton, Takahashi, Delworth, Zeng, Vallis, J. Clim 2010

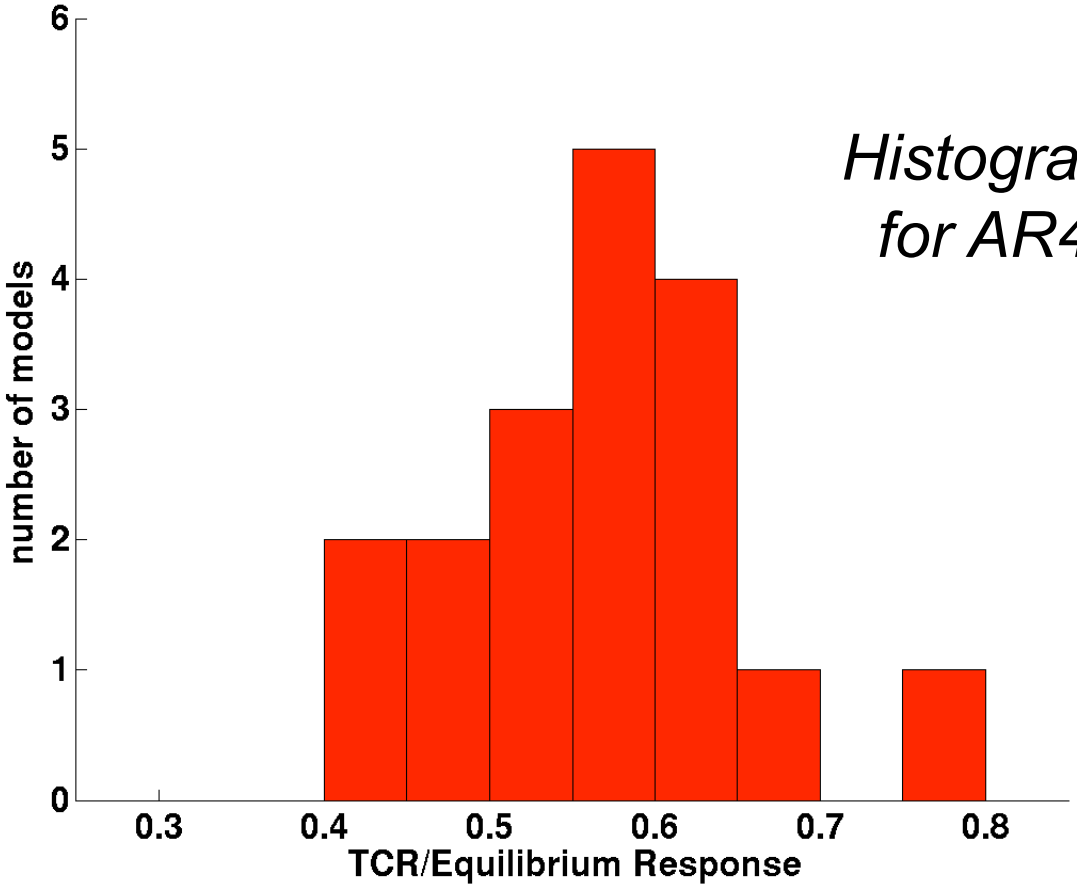
Equilibrium climate sensitivity:
Double the CO_2 and wait for the system to equilibrate

Transient climate response:
Increase CO_2 1%/yr and examine climate at the time of doubling

Typical setup – increase till doubling – then hold constant



After CO2 stabilized, warming of near surface can be thought of as due to reduction in heat uptake



Histogram of TCR/T_{EQ} for AR4 models

Increase CO2 by 1%/yr ; global mean warming at the time of doubling
= Transient Climate Response (TCR)

$$c_F \frac{dT}{dt} = -\beta T - \gamma(T - T_D) + F$$

$$c_D \frac{dT_D}{dt} = \gamma(T - T_D)$$

Mixed layer Heat capacity

Deep ocean heat capacity

Heat exchange between mixed layer and deep ocean

forcing

$$T = T_D = \frac{F}{\beta}$$ *in equilibrium*

$$c_F \frac{dT}{dt} = -\beta T - \gamma(T - T_D) + F$$

$$c_D \frac{dT_D}{dt} = \gamma(T - T_D)$$

Forcing varies on time scales longer than $\tau_F = \dfrac{c_F}{\beta + \gamma}$

$$\Rightarrow T \approx \frac{F}{\beta + \gamma} + \frac{\gamma T_D}{\beta + \gamma}$$

$$\Rightarrow c_D \frac{dT_D}{dt} = -\frac{\beta\gamma}{\beta + \gamma} T_D + \frac{\gamma}{\beta + \gamma} F$$

Forcing varies on time scales longer than $\tau_F = \dfrac{c_F}{\beta + \gamma}$

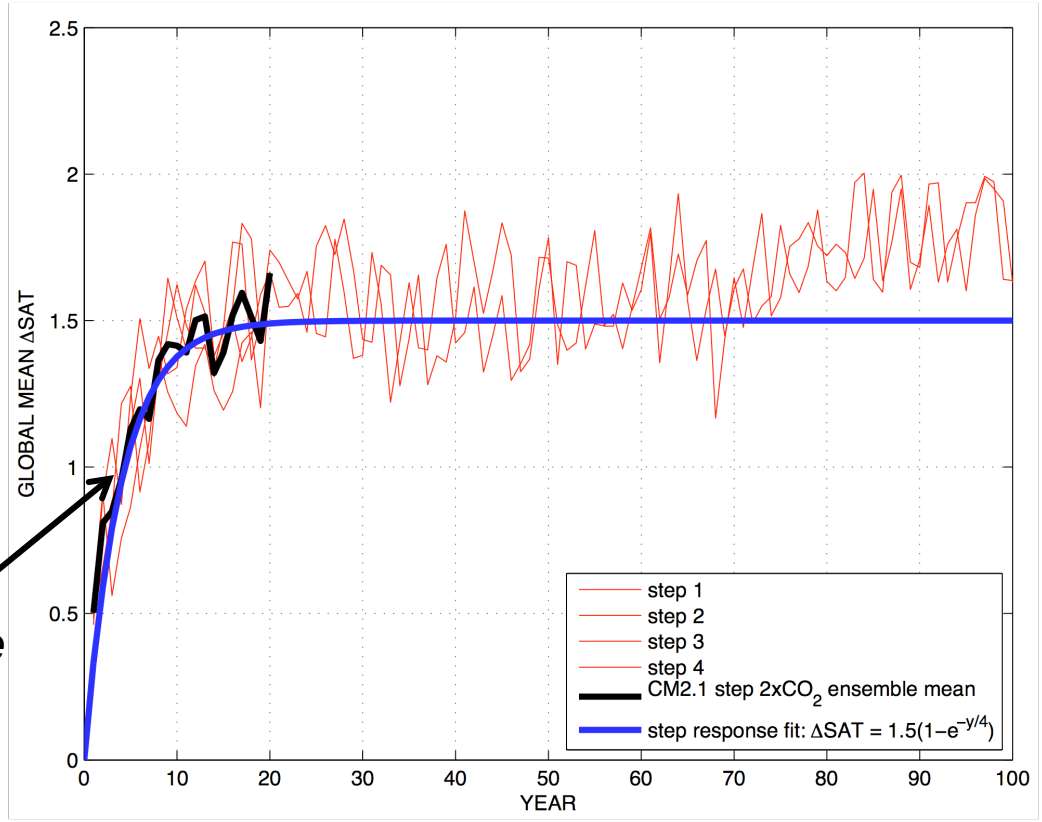
and time scales shorter than $\tau_D = \dfrac{c_D}{\beta}\dfrac{\beta + \gamma}{\gamma}$

"Intermediate regime"

$$\Rightarrow \quad T_D \approx 0 \qquad T \approx \frac{F}{\beta + \gamma}$$

$$TCR / T_{EQ} \approx \frac{\beta}{\beta + \gamma}$$

Response of global mean temperature in CM2.1 to instantaneous doubling of CO2
Equilibrium sensitivity 3.4K
Transient response 1.5K

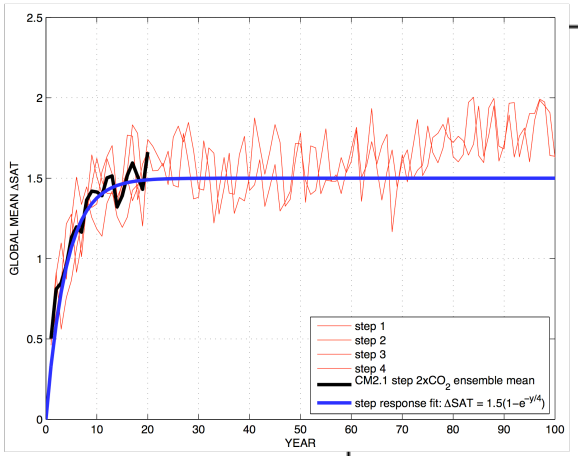


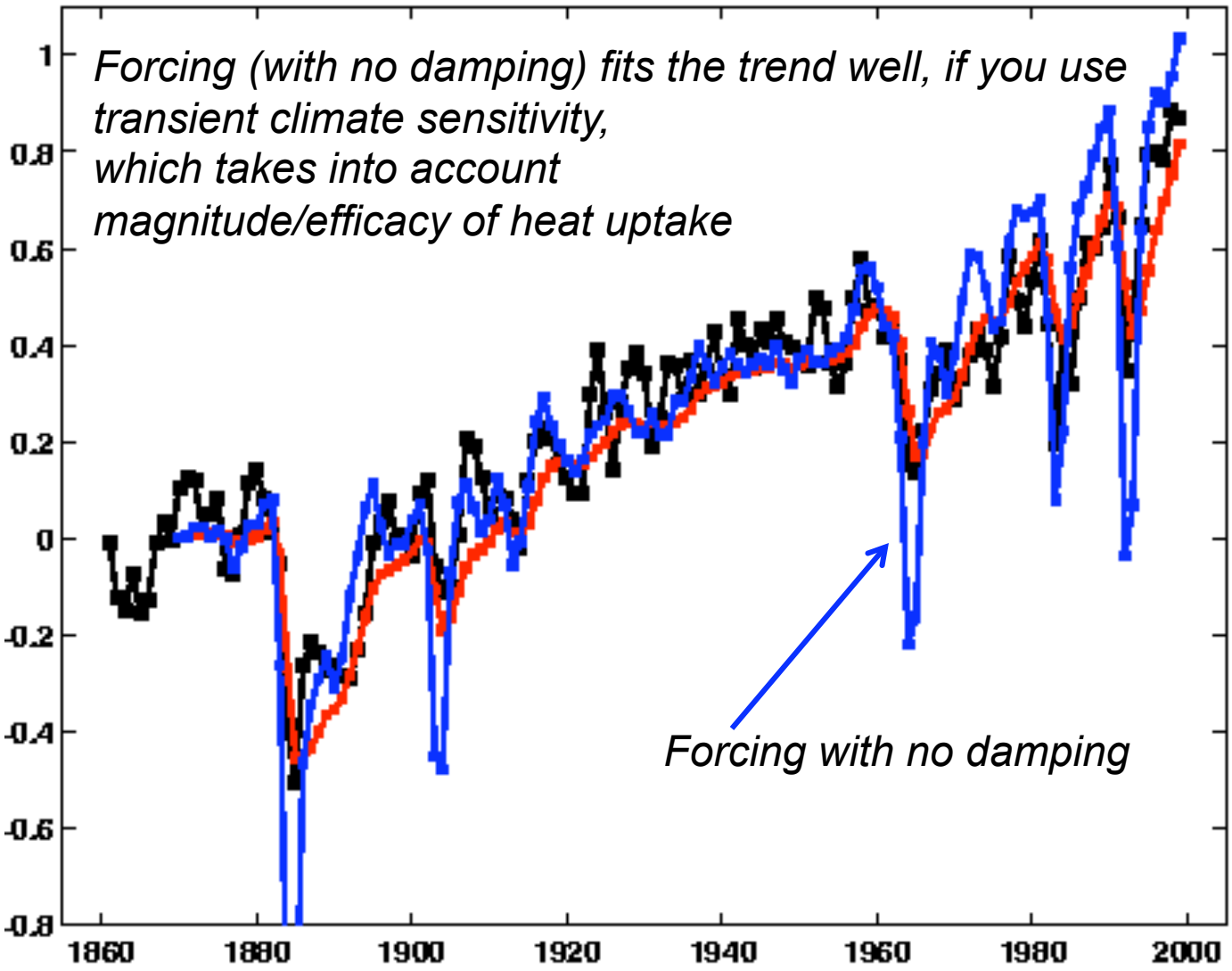
Slow response evident only after 80 yrs

Fast response

$$T = (1.5K)e^{-t/(4\,yrs)}$$

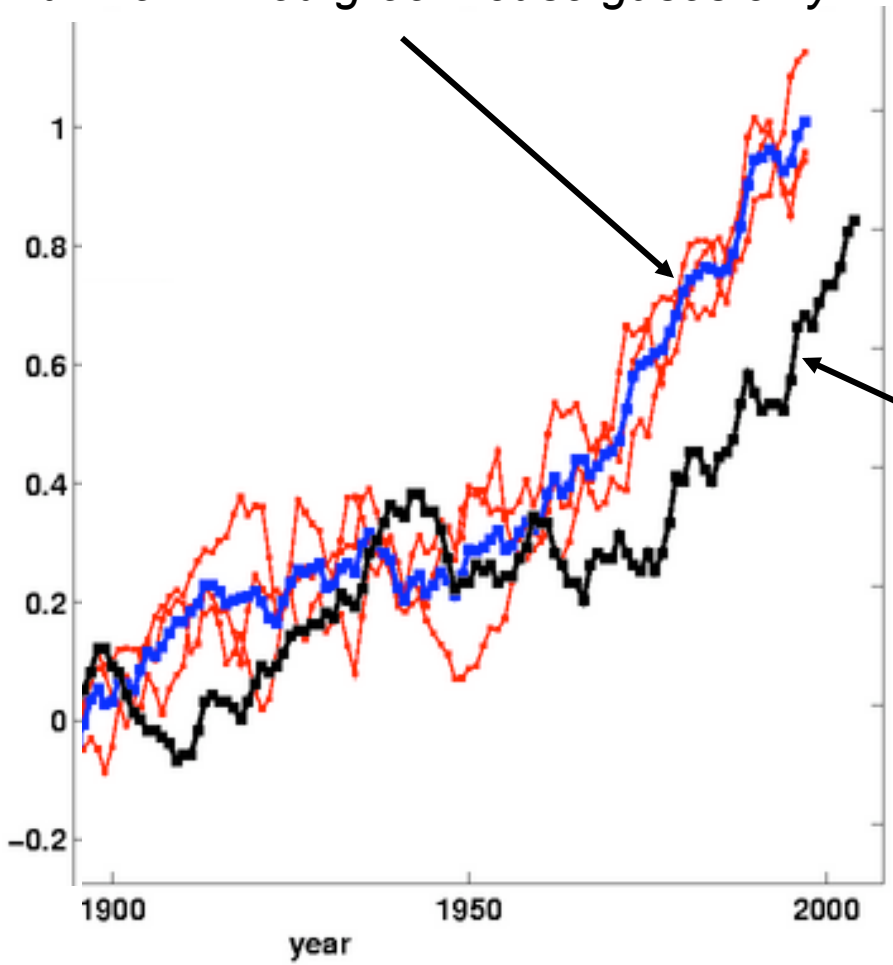
$$C\frac{dT}{dt} = F - (\beta + \gamma)T; \quad \beta + \gamma = 1.6 \ \ Wm^{-2}/K; \qquad \frac{C}{\beta + \gamma} = 4\,years$$



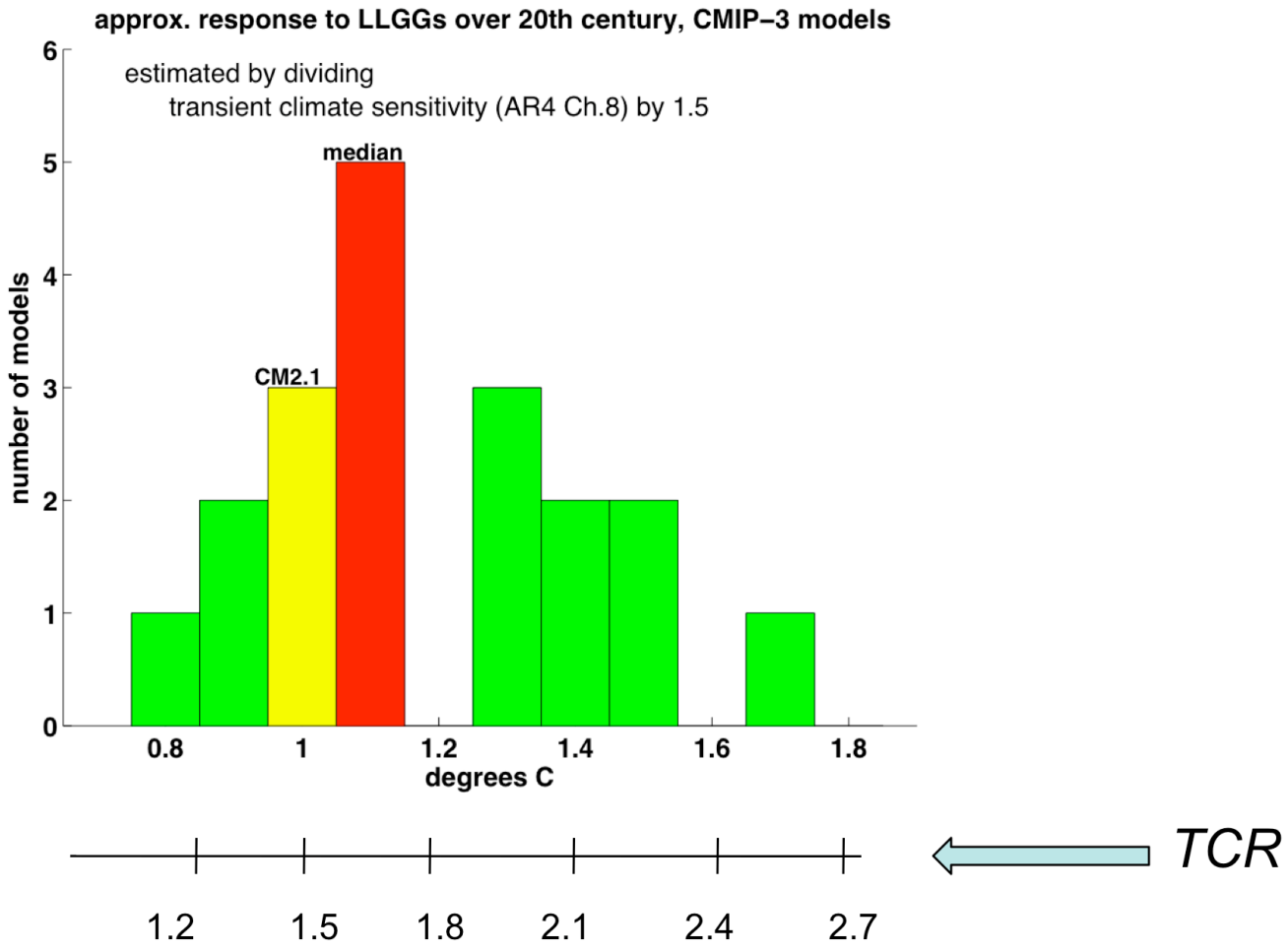

Forcing (with no damping) fits the trend well, if you use transient climate sensitivity, which takes into account magnitude/efficacy of heat uptake
Forcing with no damping
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
1860
1880
1900
1920
1940
1960
1980
2000

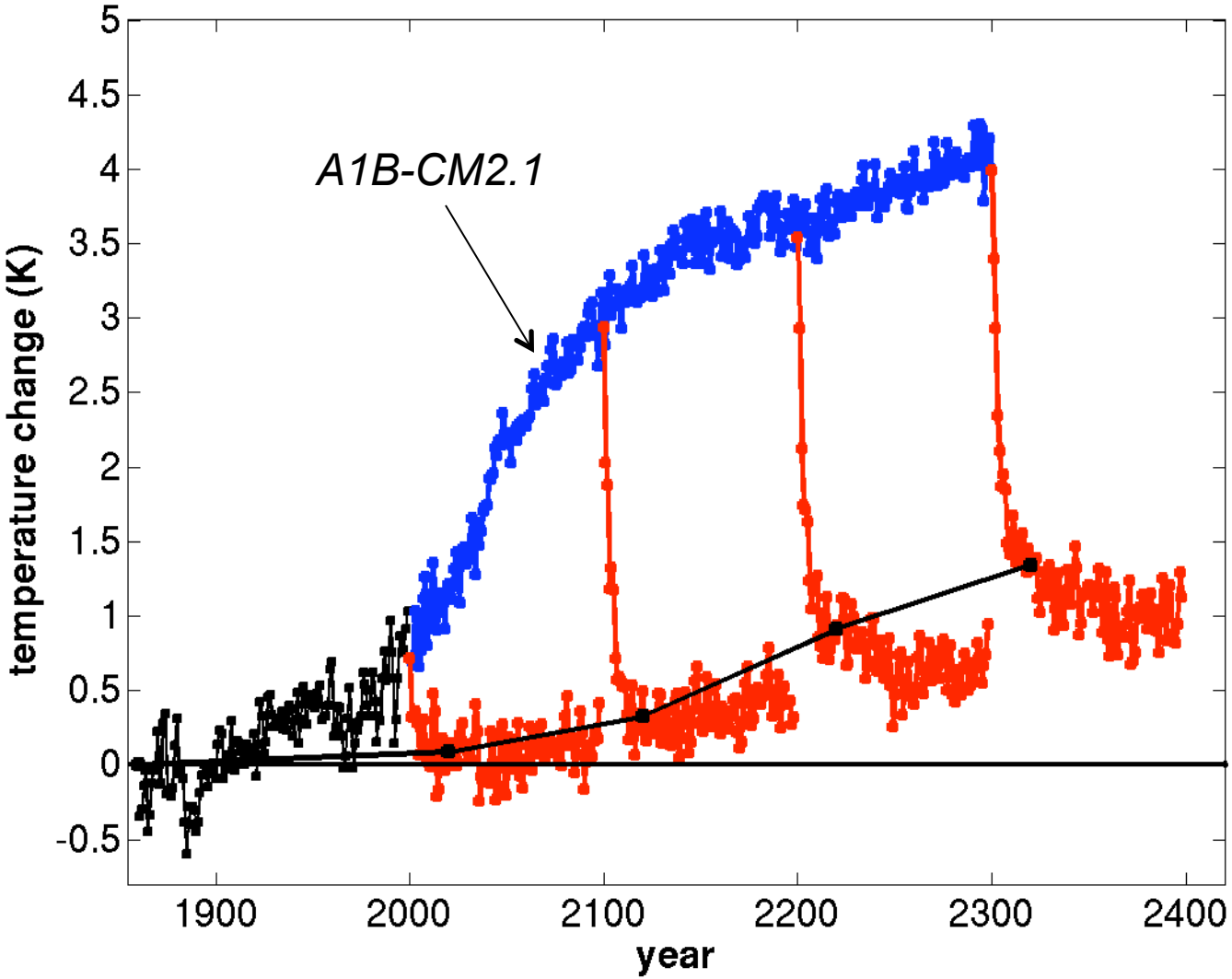
GFDL's CM2.1 with well-mixed greenhouse gases only

Global mean temperature change



Observations (GISS)


approx. response to LLGGs over 20th century, CMIP–3 models
estimated by dividing
transient climate sensitivity (AR4 Ch.8) by 1.5
median
CM2.1
number of models
0
1
2
3
4
5
6
0.8
1
1.2
1.4
1.6
1.8
degrees C
1.2
1.5
1.8
2.1
2.4
2.7
TCR


A1B-CM2.1
temperature change (K)
year
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
1900
2000
2100
2200
2300
2400

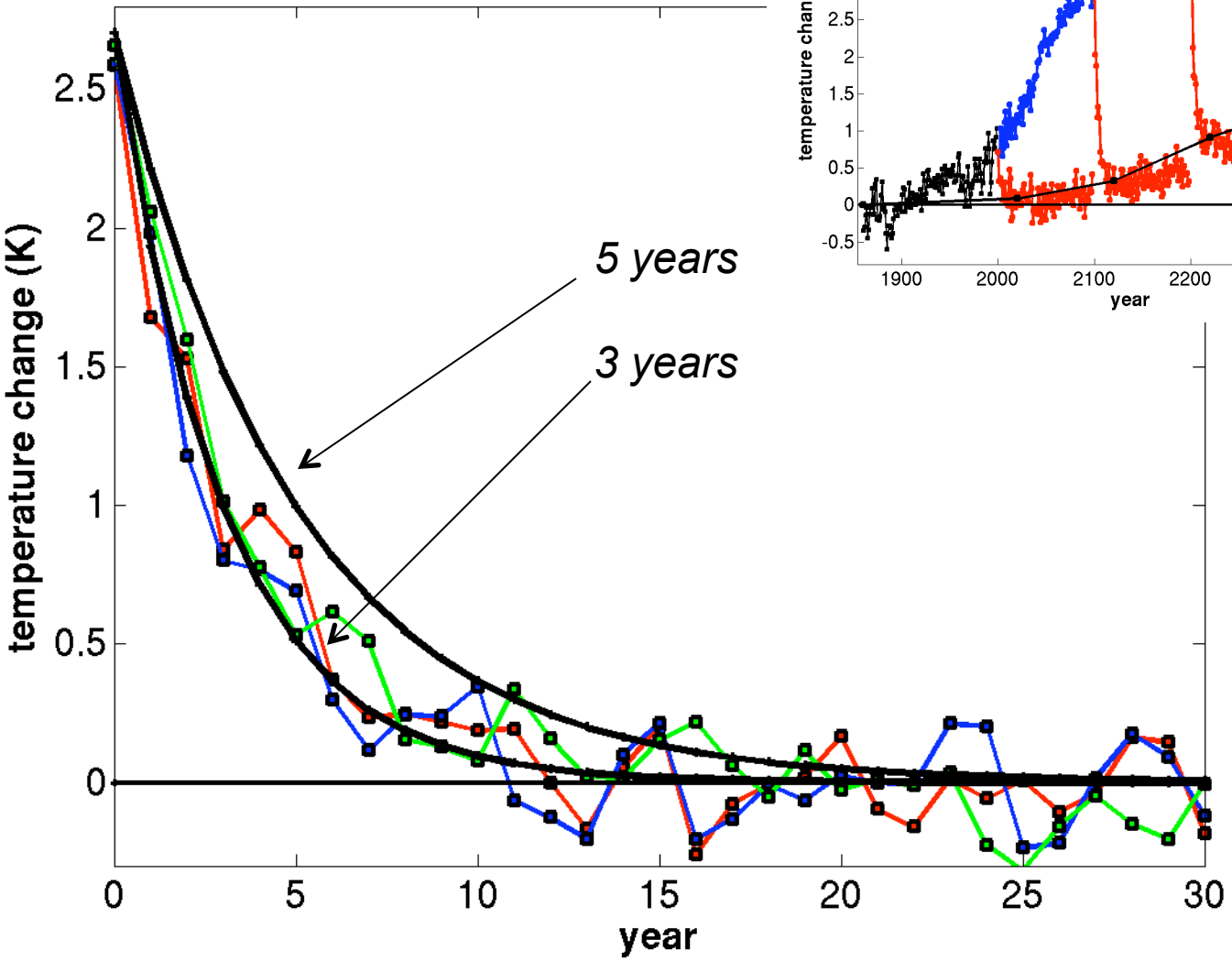
$$T \approx \frac{F}{\beta + \gamma} + \frac{\gamma T_D}{\beta + \gamma}$$

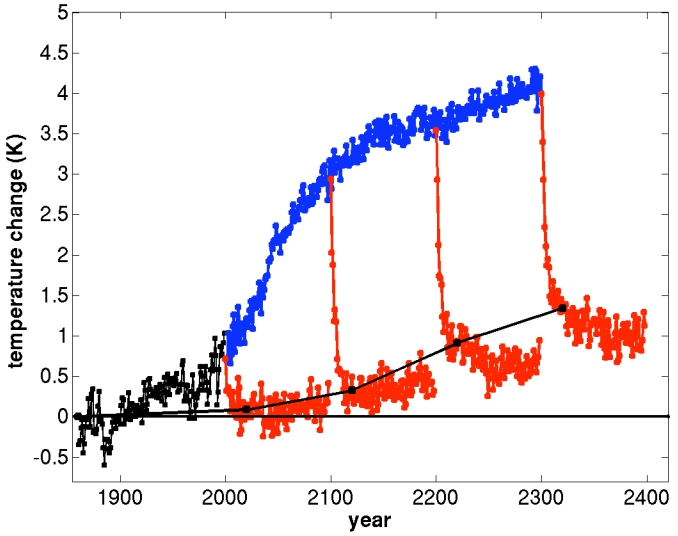
Return instantaneously to pre-industrial forcing
(F = 0)

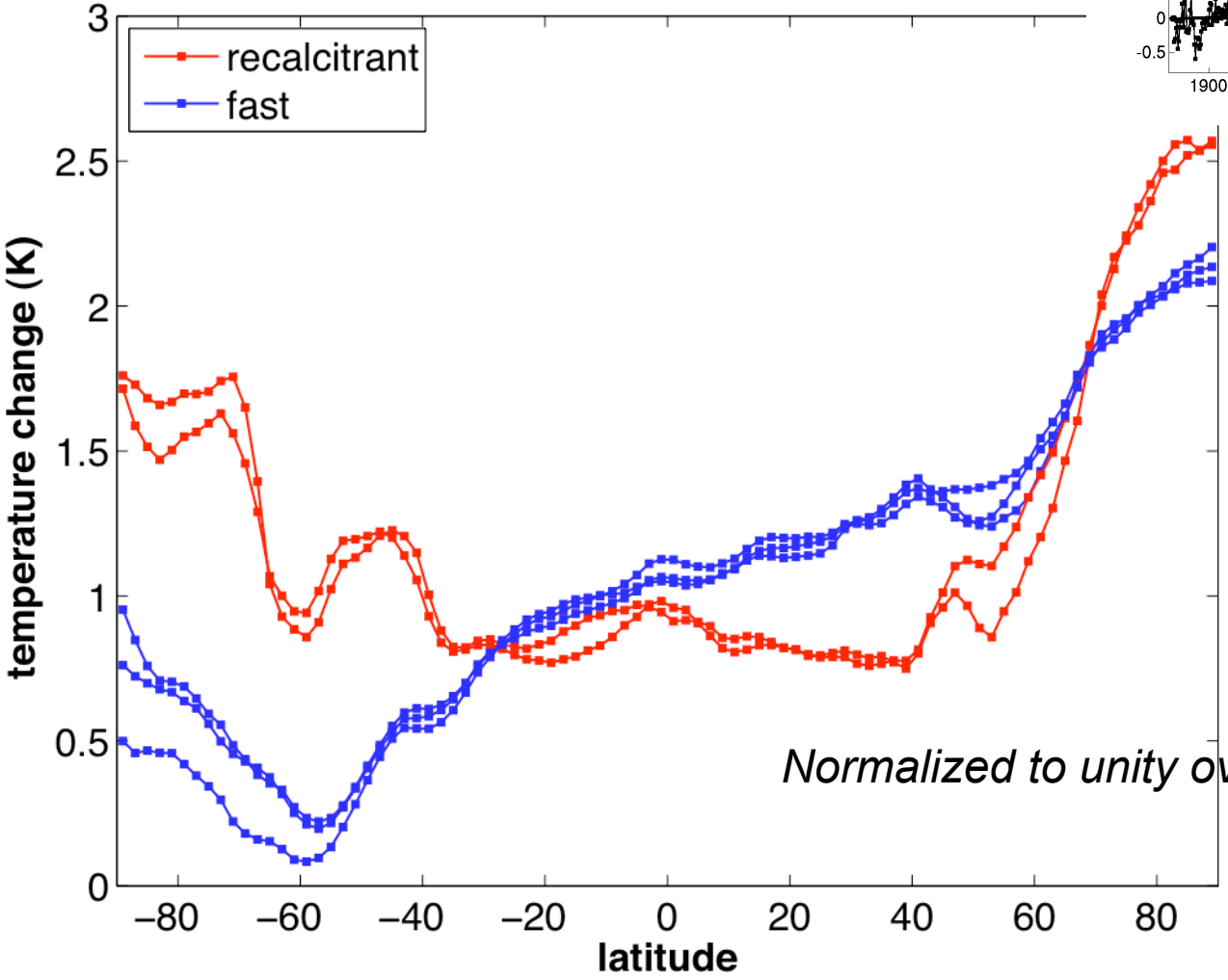
$$\Rightarrow T \approx \frac{\gamma T_D}{\beta + \gamma}$$

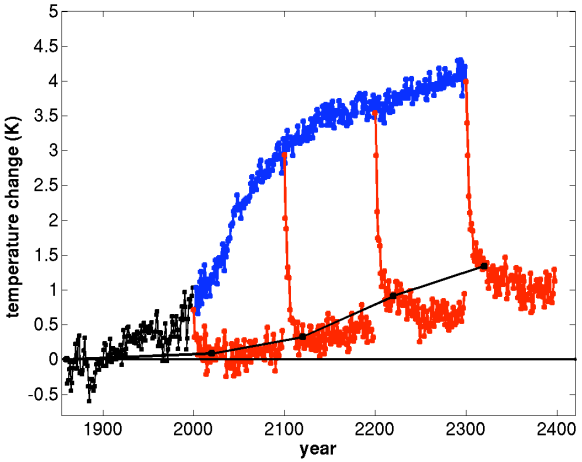
the "Recalcitrant" warming

Relaxation to recalcitrant warming



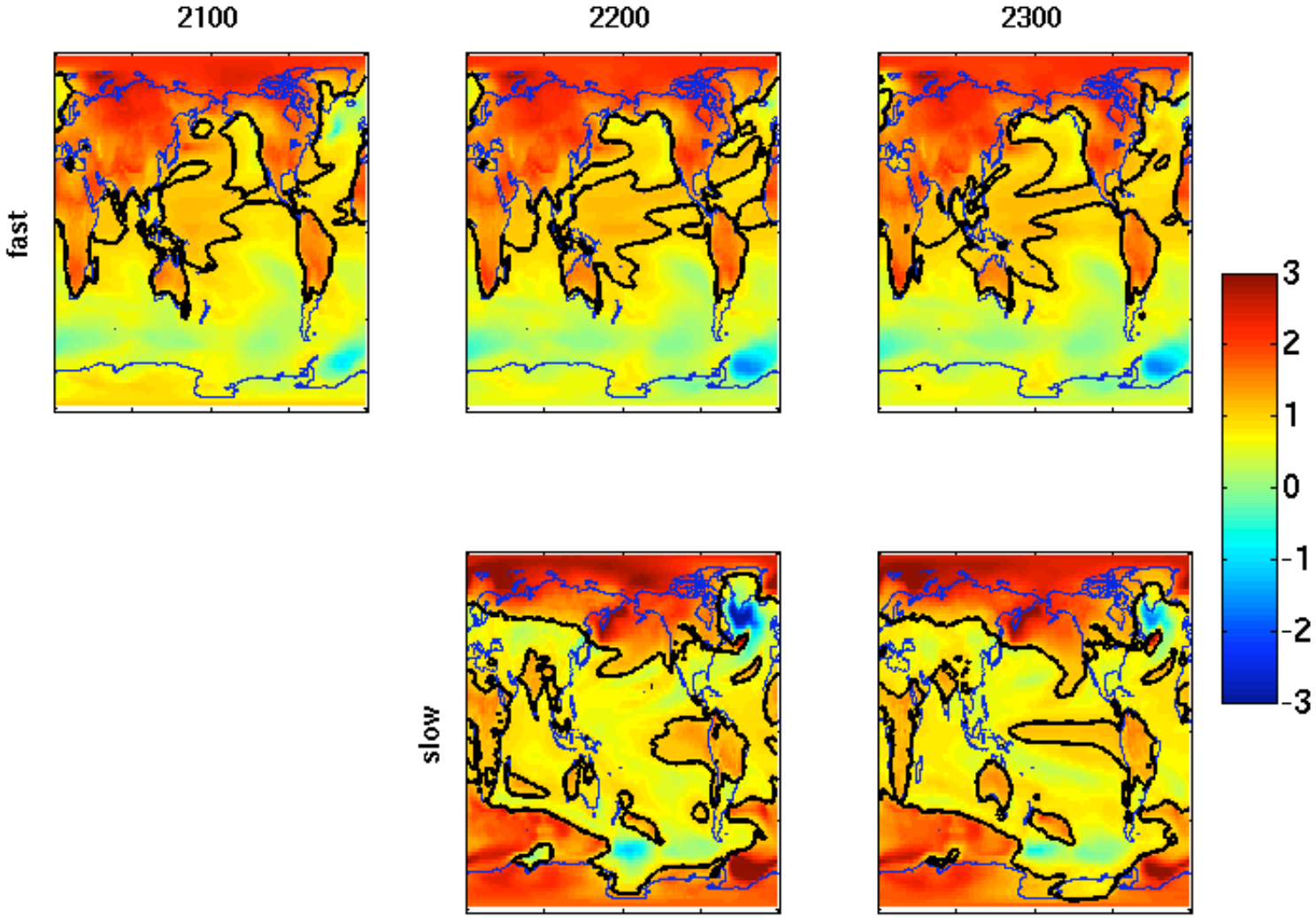


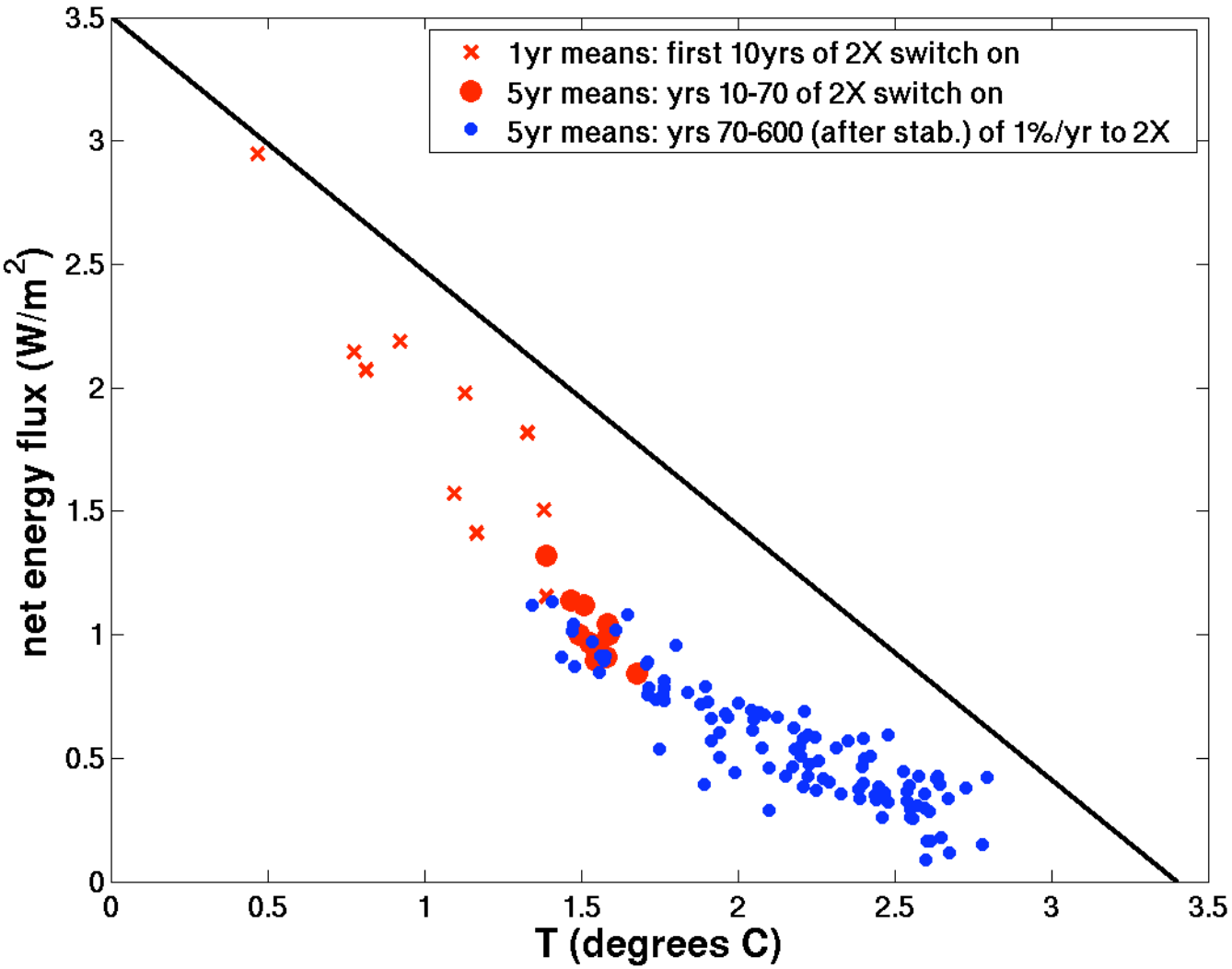




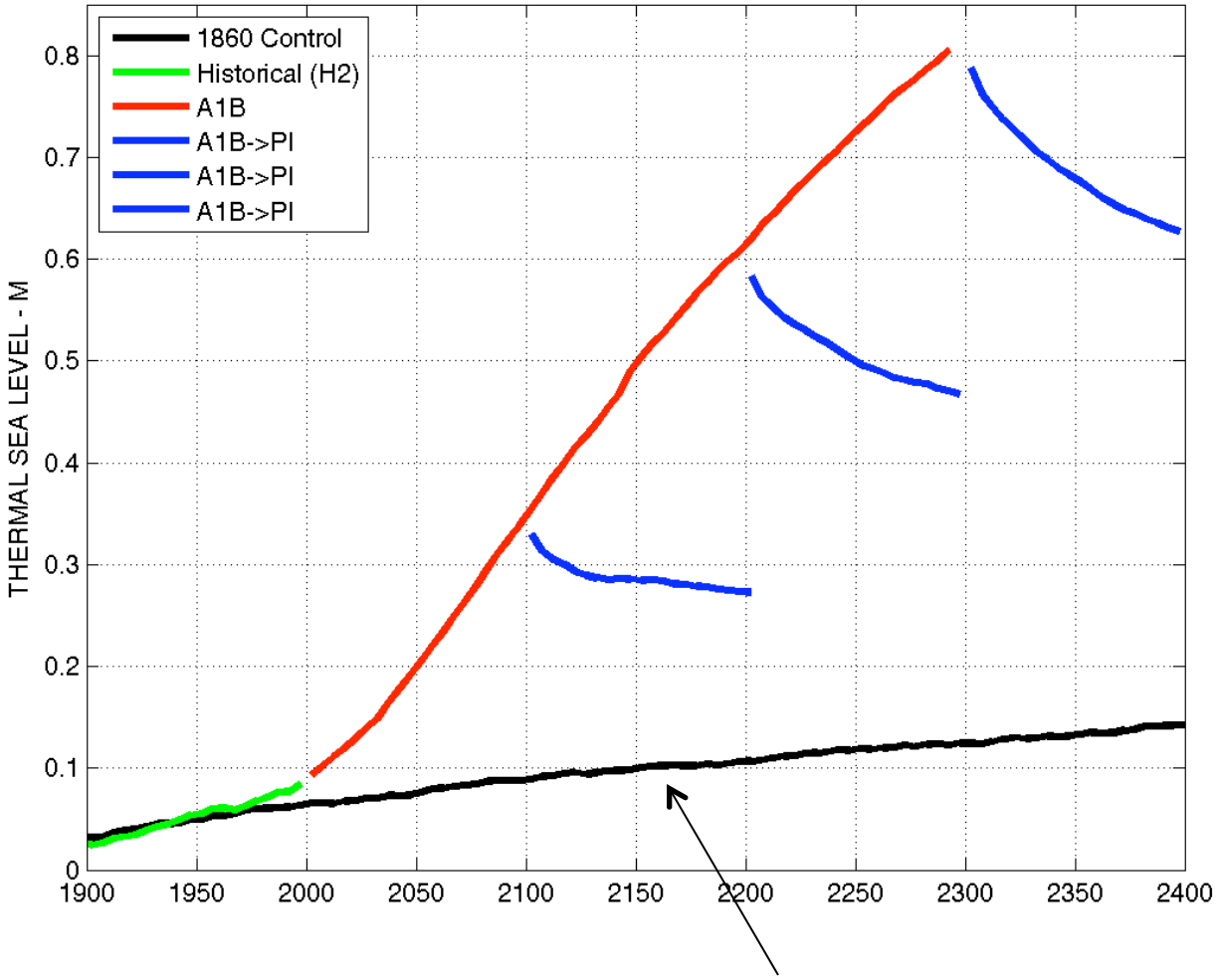
Normalized to unity over the globe

Normalized to unity over the globe



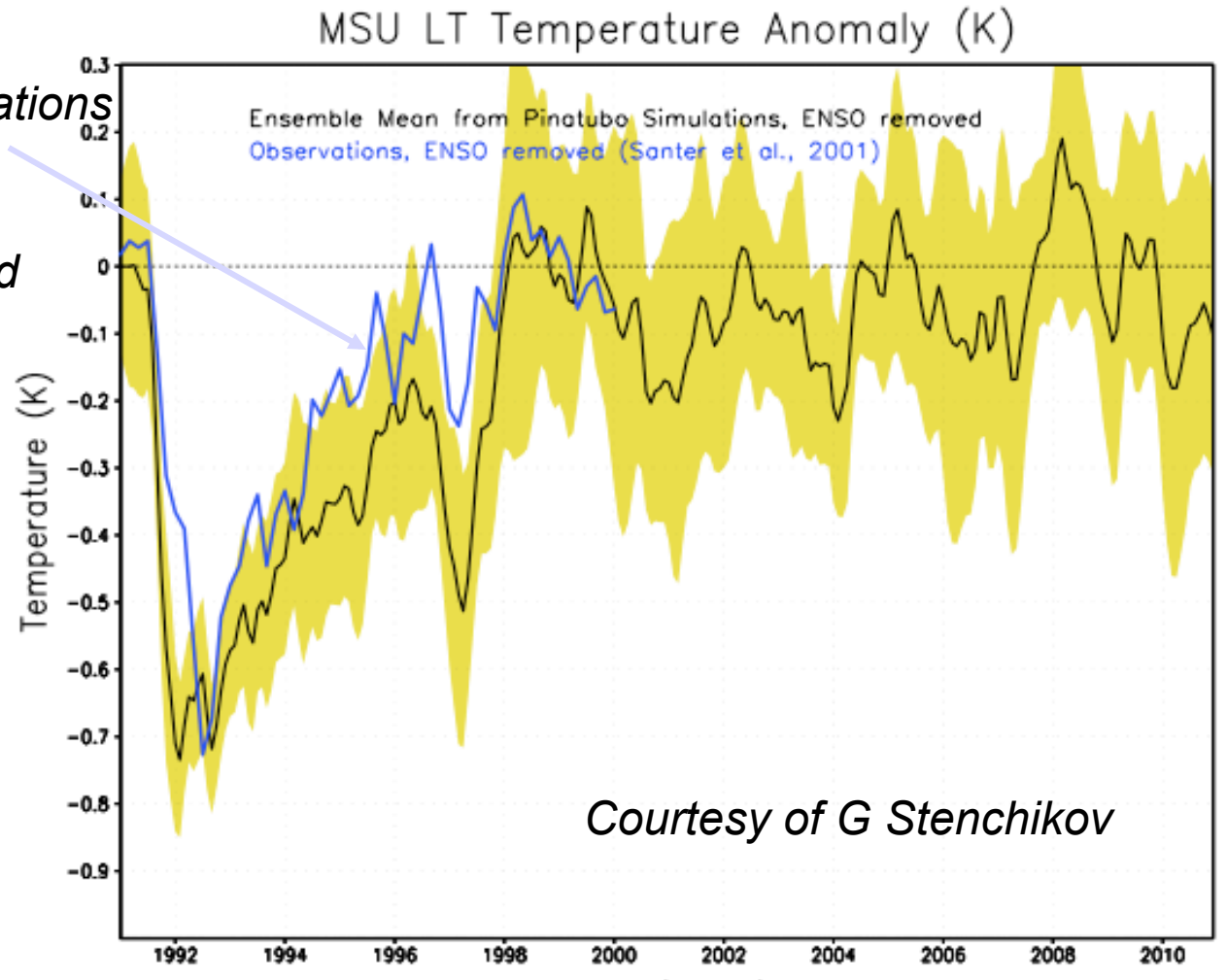

1yr means: first 10yrs of 2X switch on
5yr means: yrs 10-70 of 2X switch on
5yr means: yrs 70-600 (after stab.) of 1%/yr to 2X
net energy flux (W/m2)
T (degrees C)
0
0.5
1
1.5
2
2.5
3
3.5

Sea level response due to thermal expansion



Control drift

Global mean cooling due to Pinatubo volcanic eruption



Observations with El Nino removed

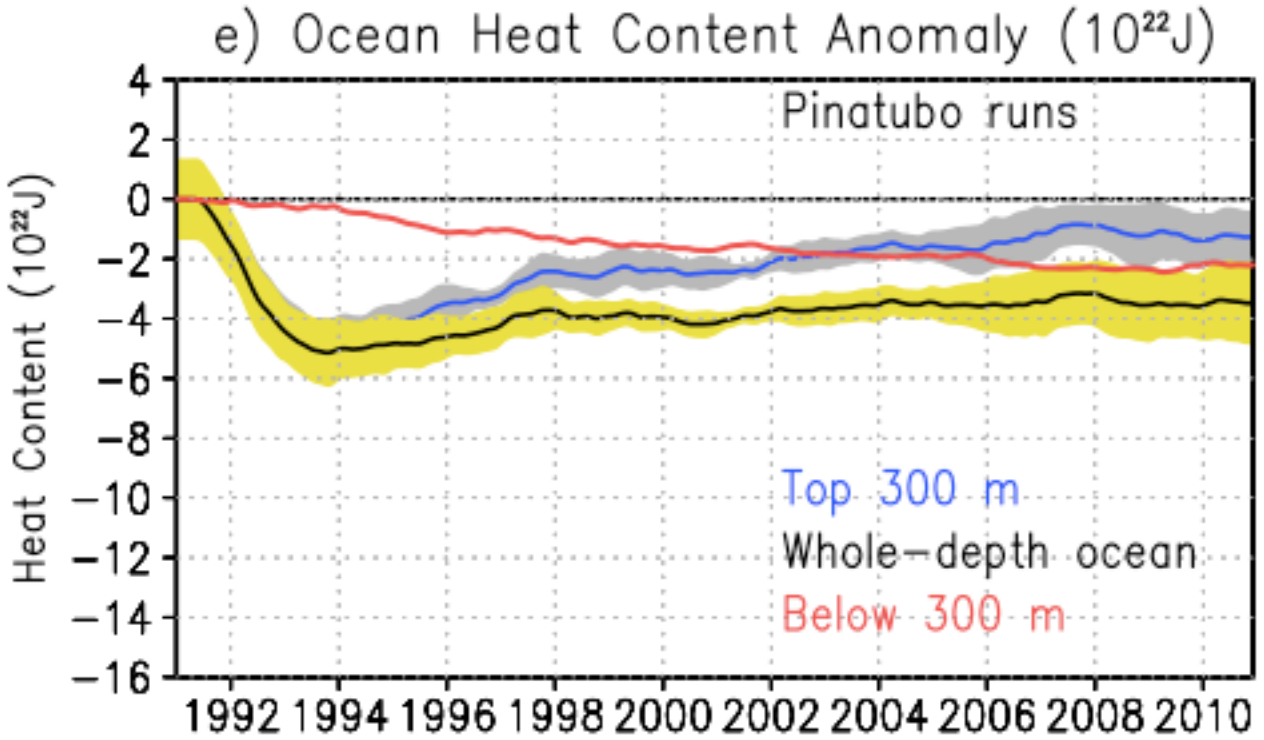
Range of ~10 Model Simulations GFDL CM2.1

Relaxation time after abrupt cooling contains information on climate sensitivity

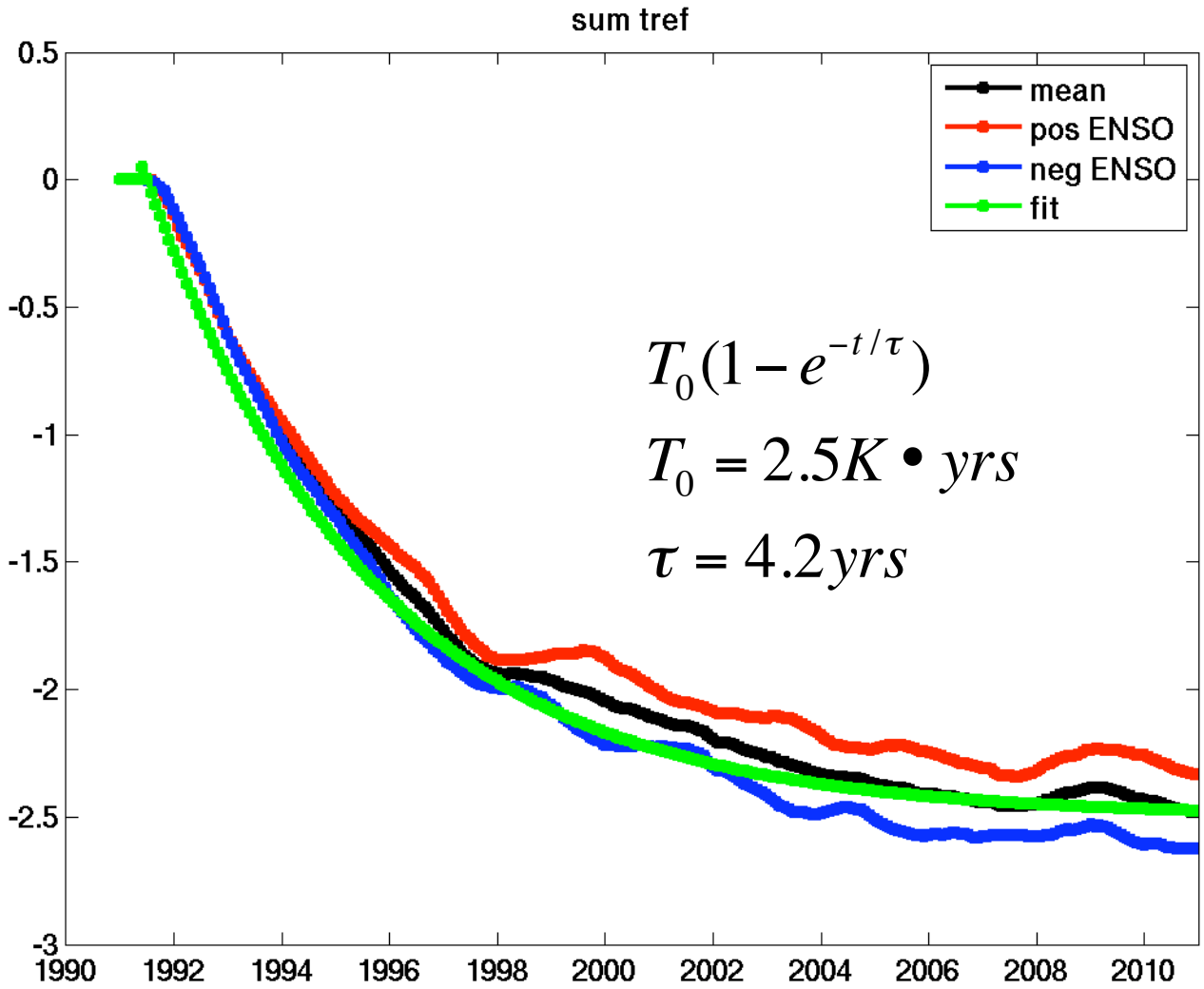
Response to pulse of forcing (volcano), F(t):

2-box model:

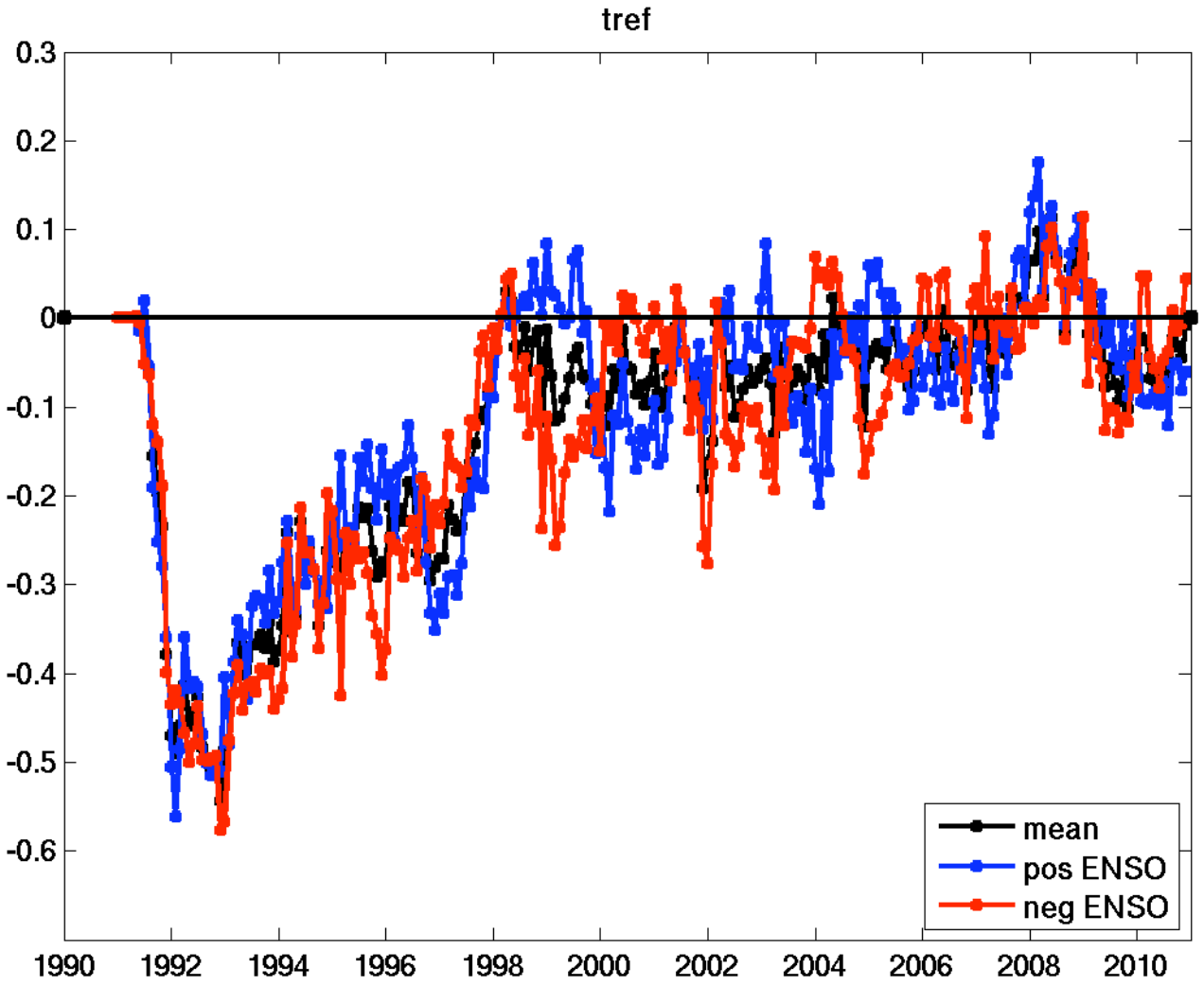
$$\int_0^{fast} T dt = \frac{\int F dt}{\beta + \gamma} \qquad \int_0^{\infty} T dt = \frac{\int F dt}{\beta}$$

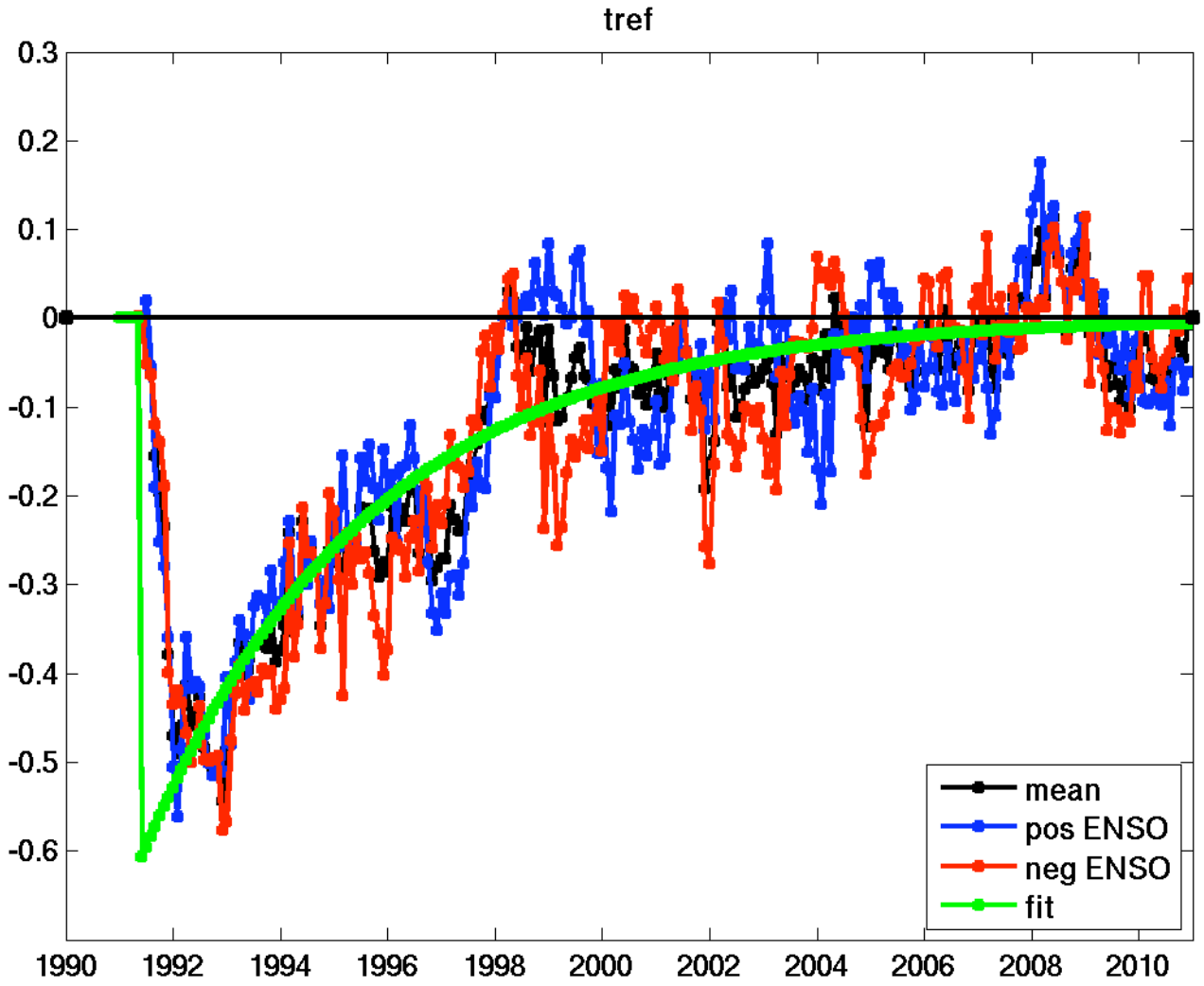


Stenchikov, et al 2009

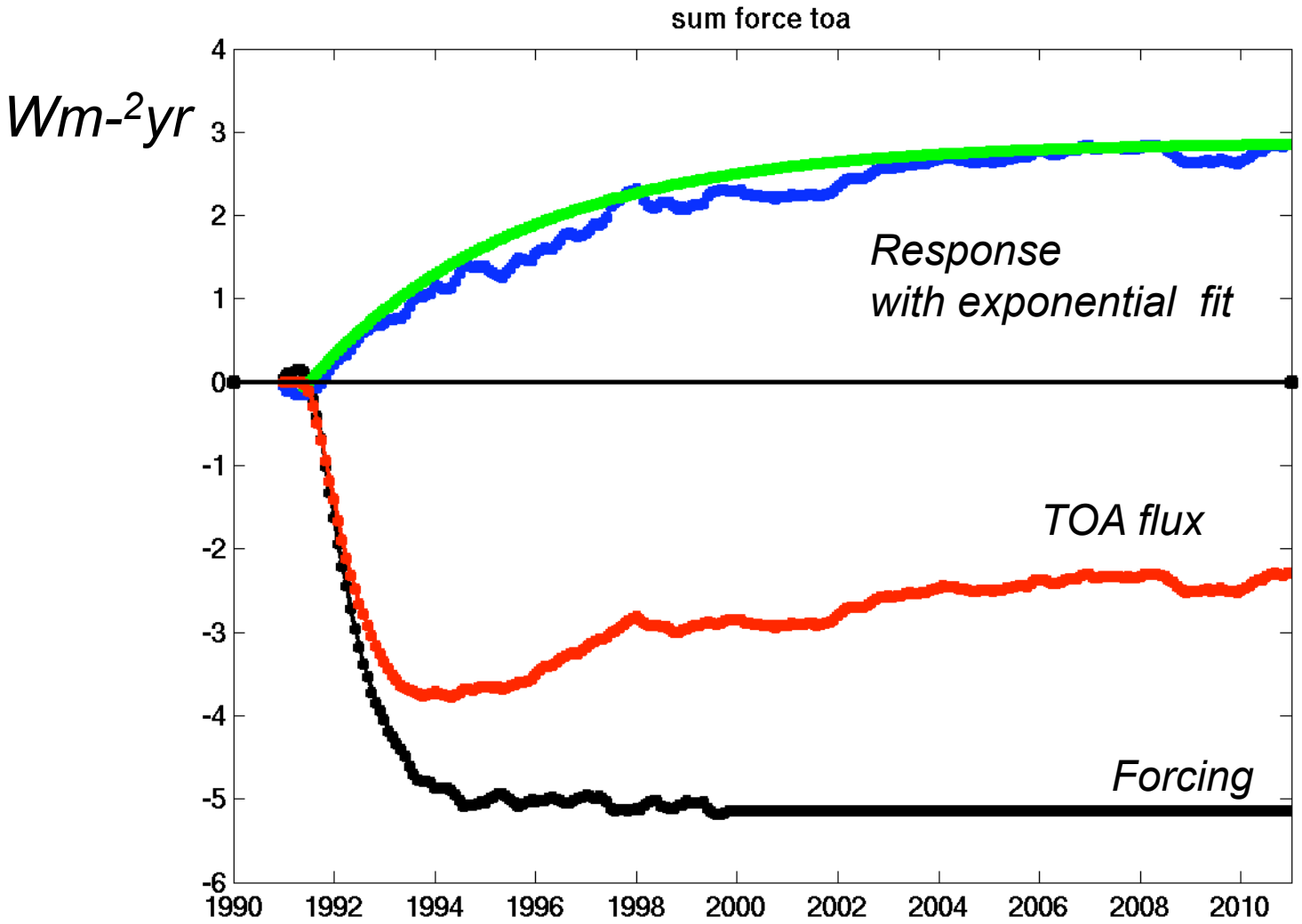

sum tref
mean
pos ENSO
neg ENSO
fit
$T_0(1-e^{-t/\tau})$
$T_0 = 2.5K \bullet yrs$
$\tau = 4.2yrs$
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010

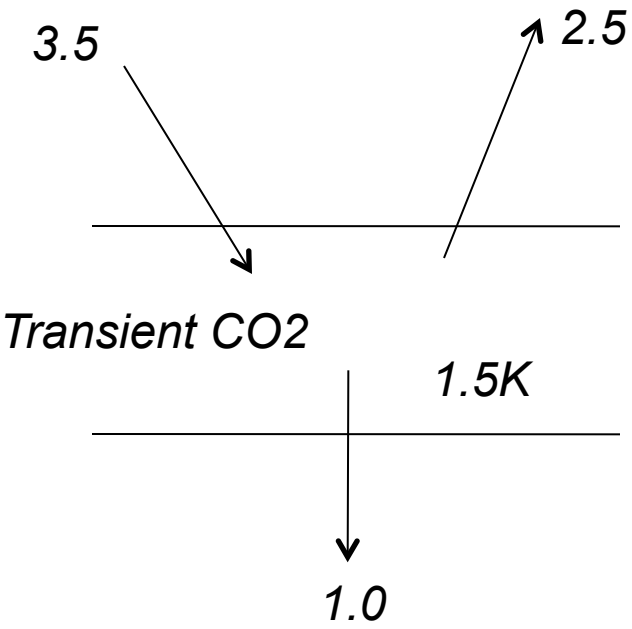
Near surface air temperature response (20 member ensemble)
Courtesy of Stenchikov, et al

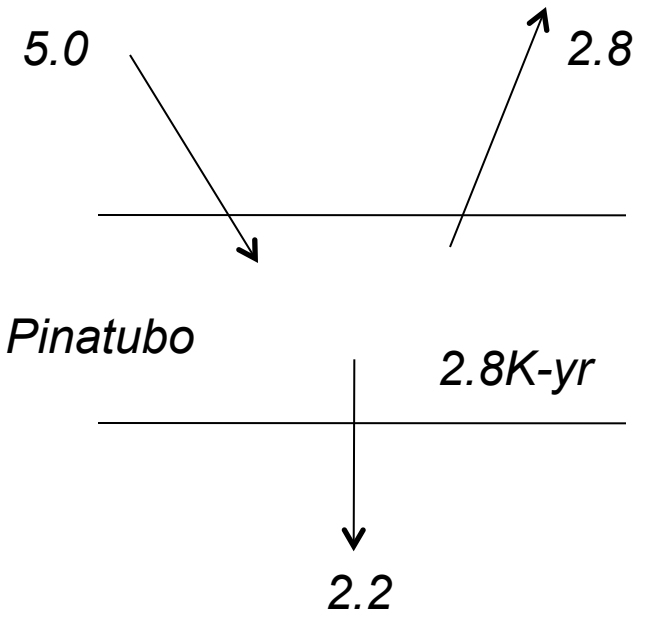



tref
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
mean
pos ENSO
neg ENSO
fit

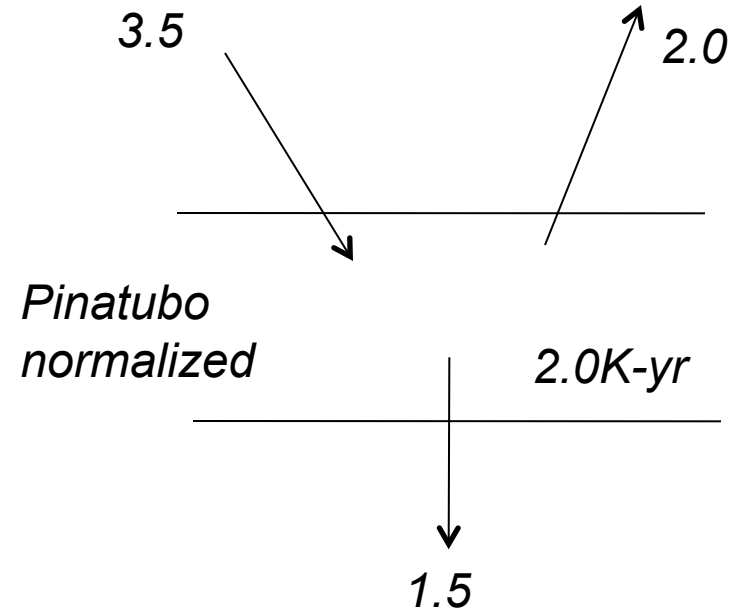
Integrated forcing and response







Pinatubo a rough guide to transient CO2 response (no direct information on equilibrium response)



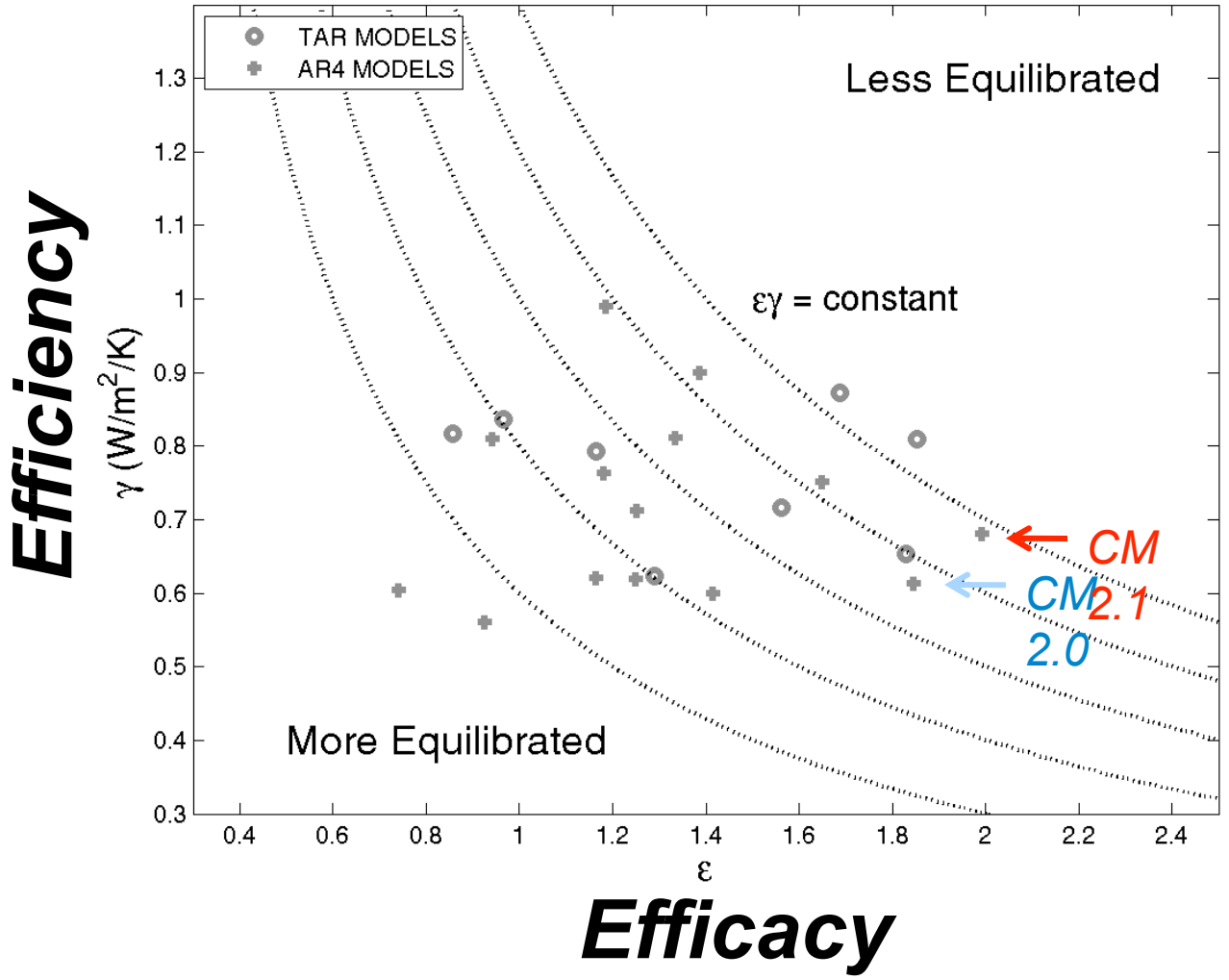
I suspect that:

Transient climate sensitivity can be constrained much more tightly that it currently is, despite the uncertainty in aerosol forcing

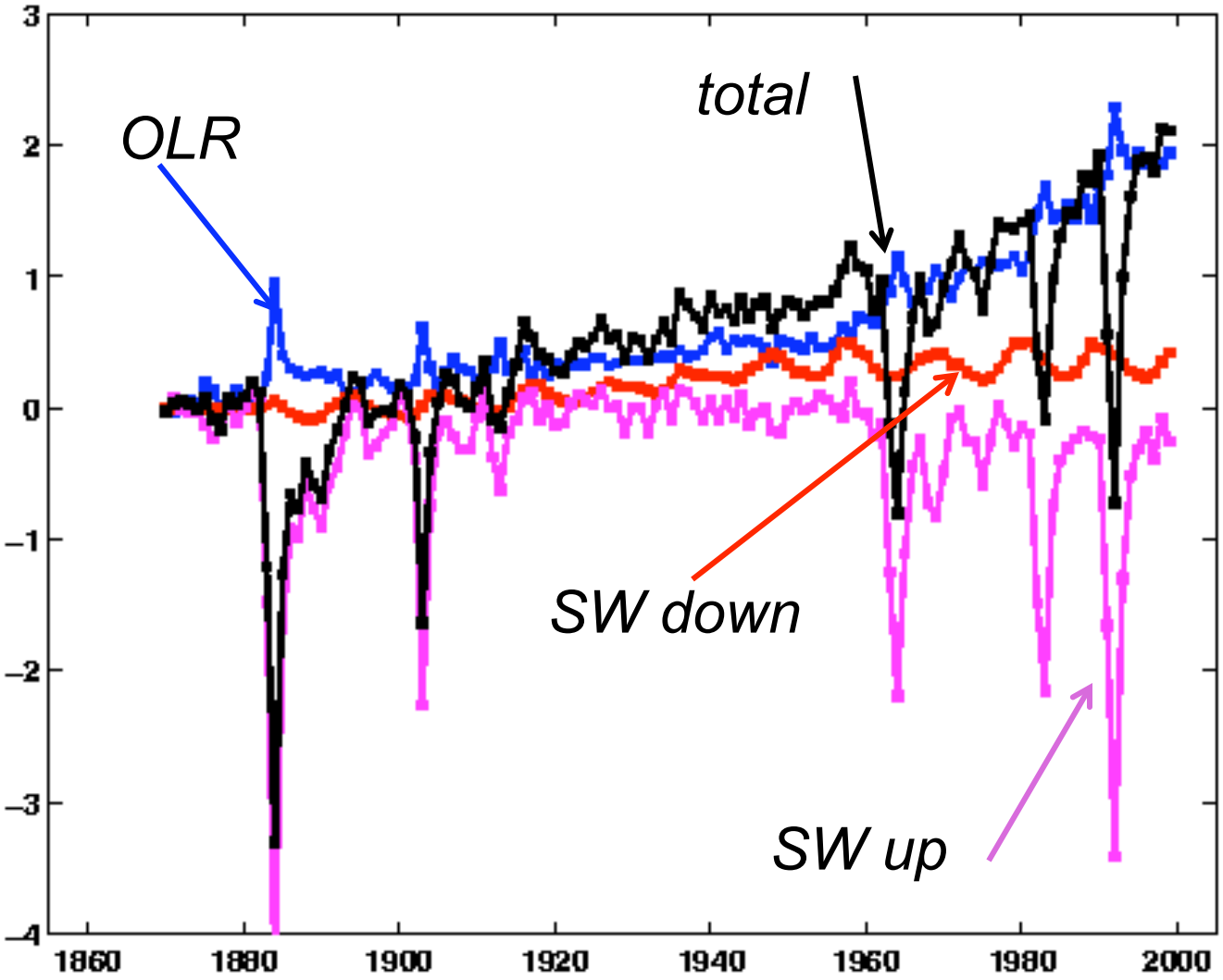
Volcanic responses will play a central role in tightening this constraint

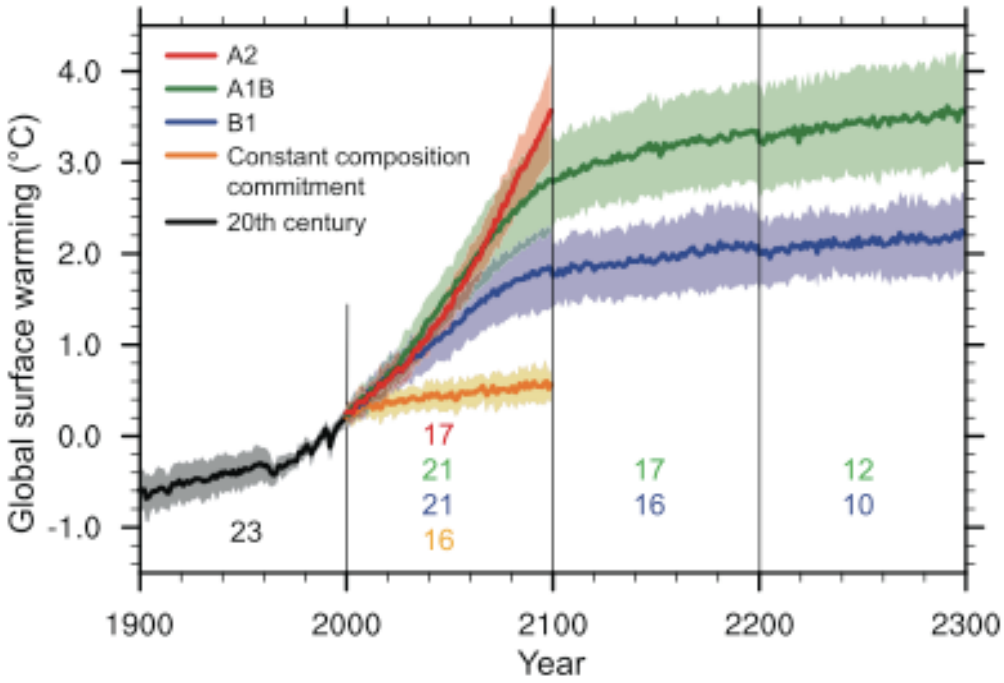
Thank you for listening, and thank you, Mike!

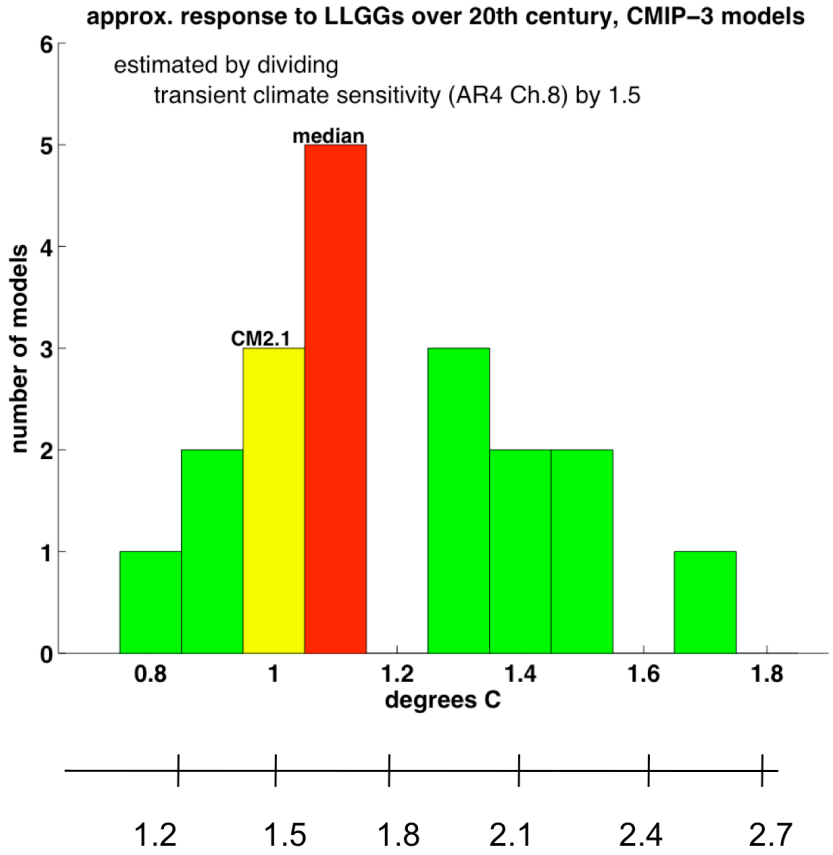
Efficacy and Efficiency



Forcing computed from differencing TOA fluxes in two runs of a model (B-A)
B = fixed SSTs with varying forcing agents; A fixed SSTs and fixed forcing agents




A2
A1B
B1
Constant composition commitment
20th century
Global surface warming (°C)
4.0
3.0
2.0
1.0
0.0
-1.0
1900
2000
2100
2200
2300
Year
23
17
21
21
16
17
16
12
10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transient climate sensitivity (AR4 Ch.8) by 1.5
median
CM2.1
number of models
0
1
2
3
4
5
6
0.8
1
1.2
1.4
1.6
1.8
degrees C
1.2
1.5
1.8
2.1
2.4
2.7
TCR