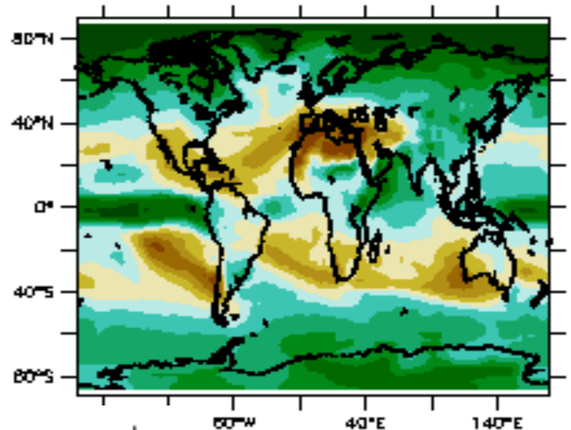
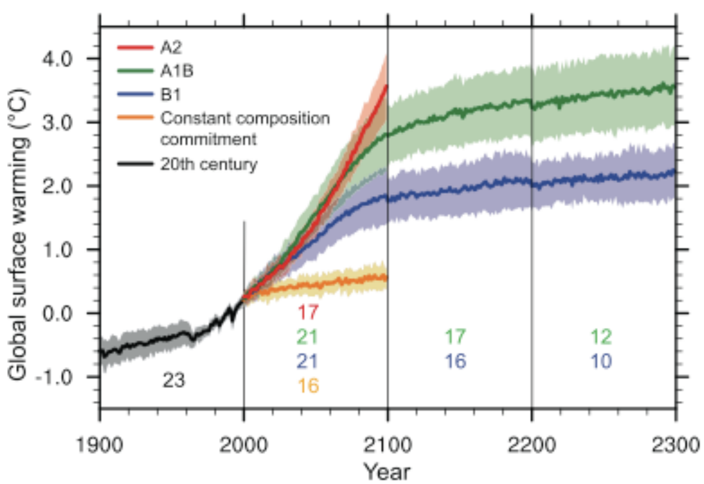
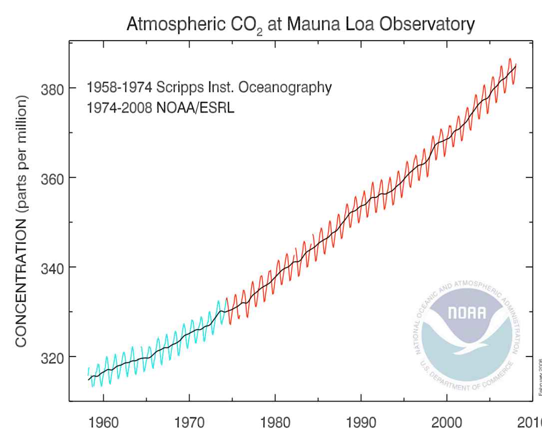
Climate Sensitivity: Linear Perspectives

Isaac Held, Jerusalem, Jan 2009

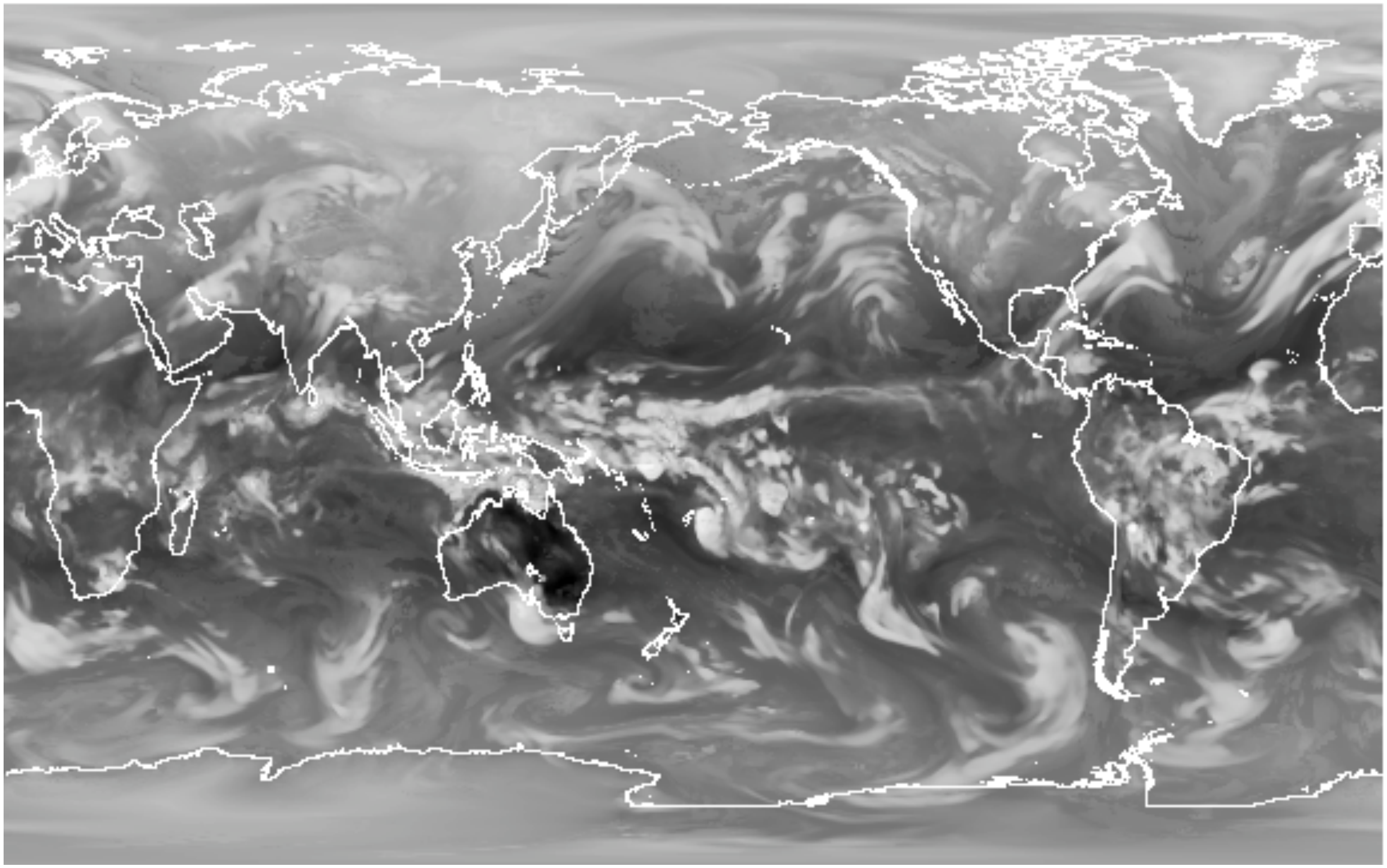




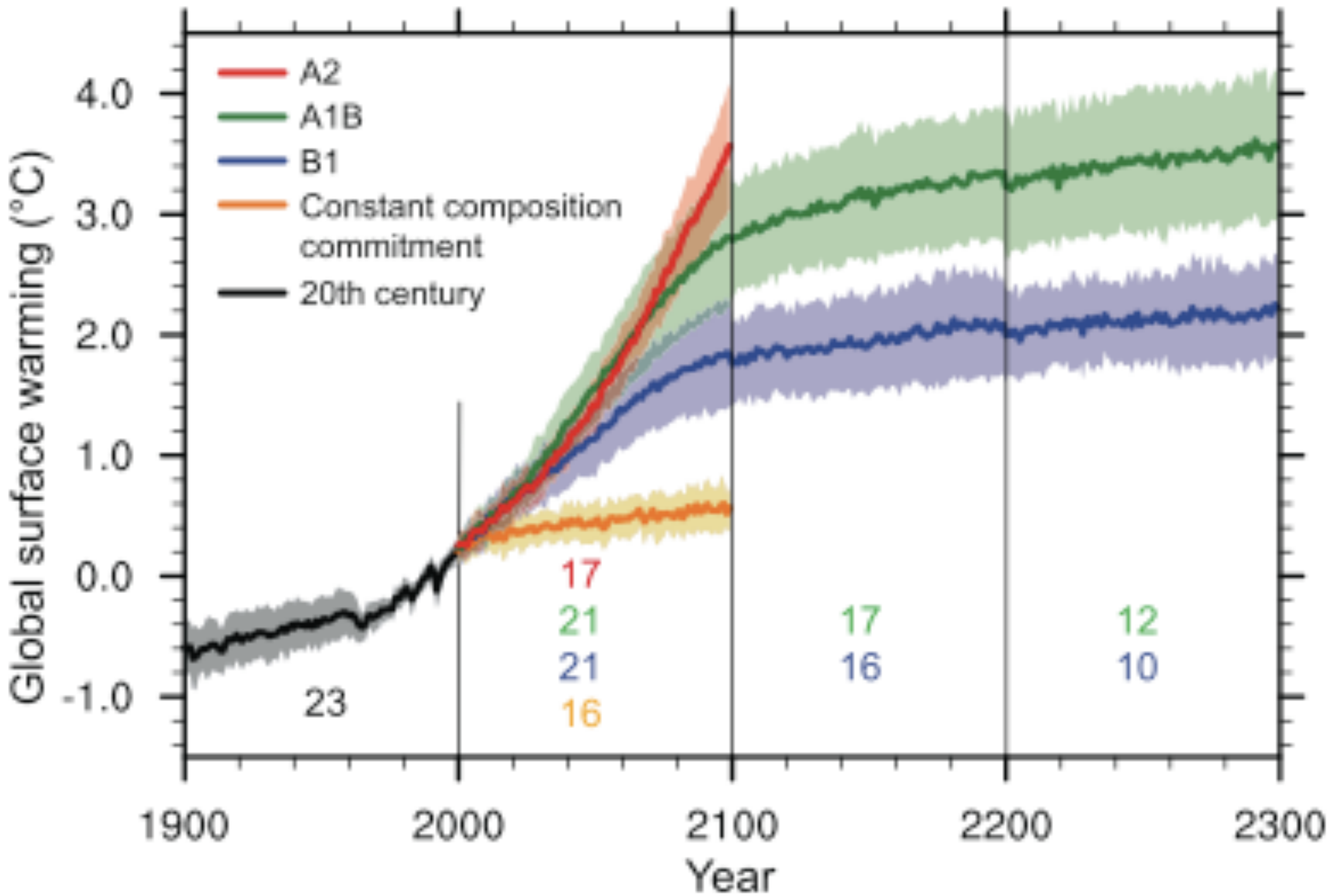


How can the response of such a complex system be "linear"?

Infrared radiation escaping to space -
- 50km model under development at GFDL

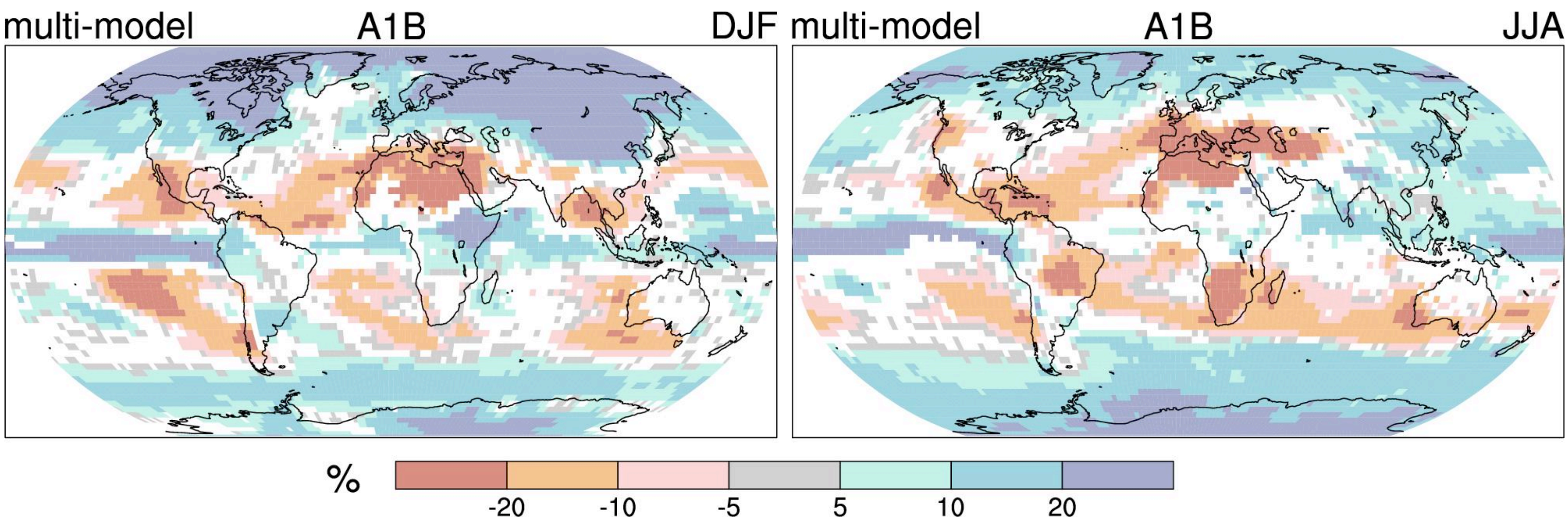


Response of global mean temperature to increasing CO2 seems simple, as one might expect from the simplest linear energy balance models



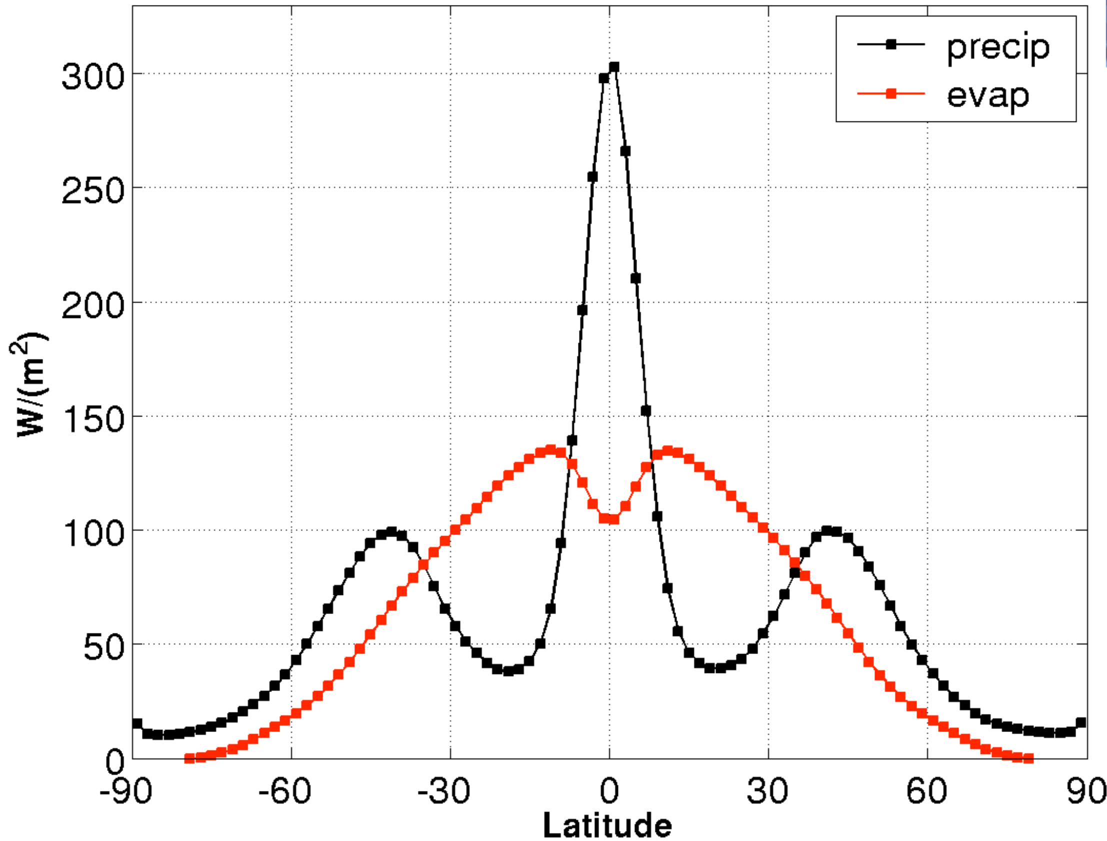
But we are not interested in global mean temperature, but rather things like the response in local precipitation

Percentage change in precipitation by end of 21st century: PCMDI-AR4 archive

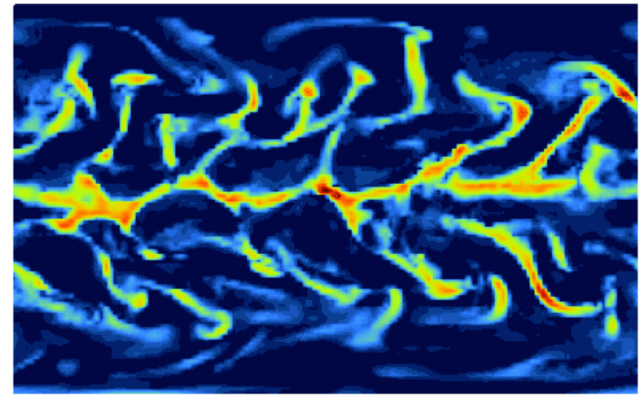


White areas => less than two thirds of the models agree on the sign of the change

Precipitation and evaporation
"Aqua_planet" climate model
(no seasons, no land surface)



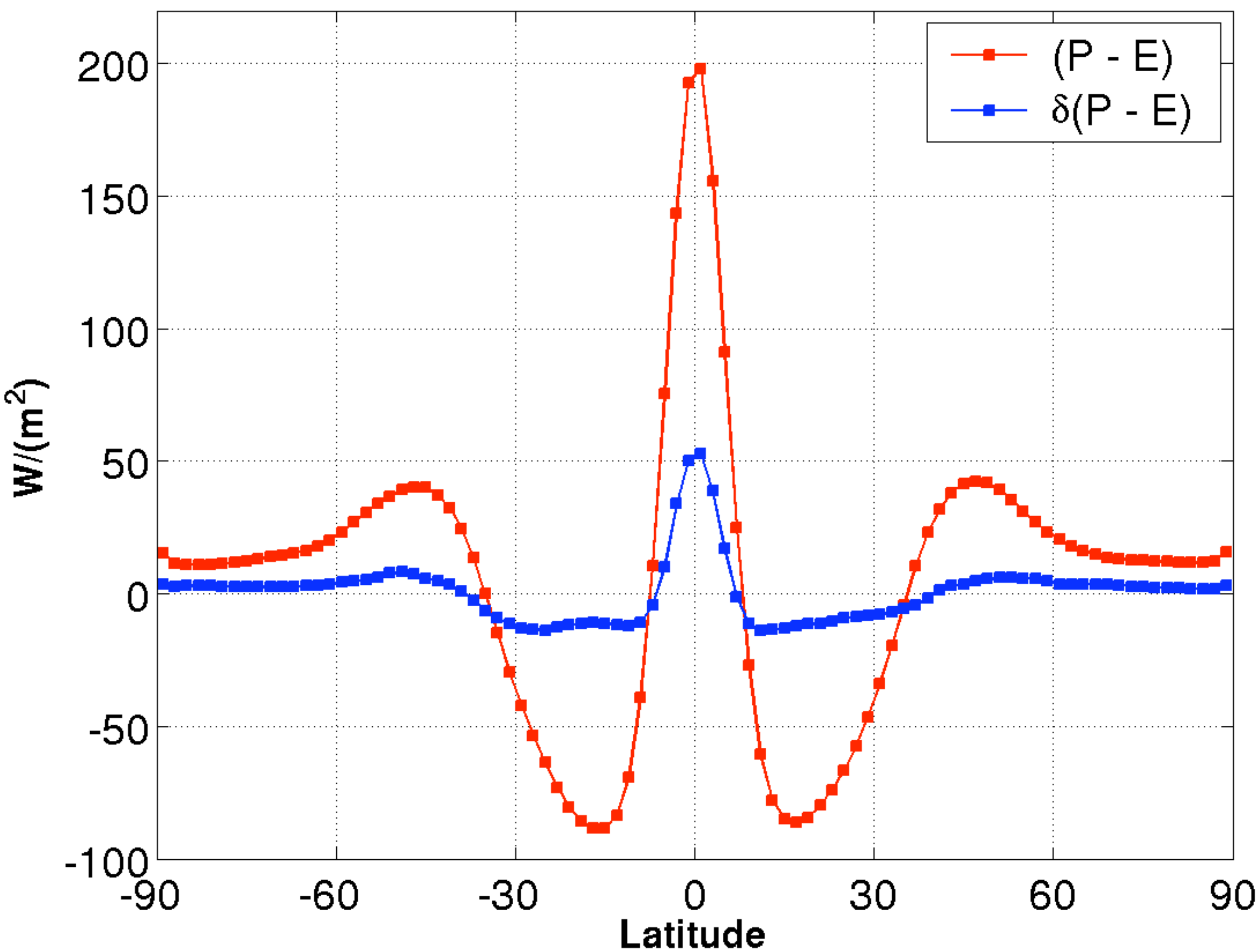
Time means



Instantaneous precip (lat,lon)

4a

Aqua planet (P – E) response to doubling of CO_2



4b

Saturation vapor pressure

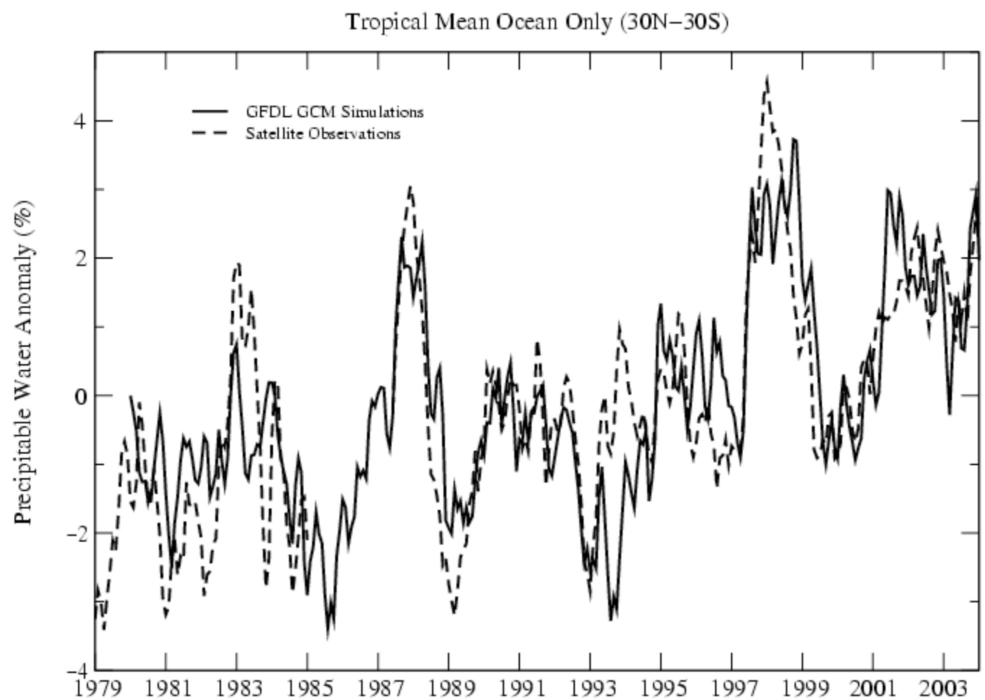
$$e_s = exp(-\frac{L}{R_v T})$$

$$\frac{1}{e_s}\frac{de_s}{dT} = \frac{L}{R_v T^2}$$

$$\frac{\delta e_s}{e_s} \approx \frac{L}{R_v T^2}\delta T \approx 0.07\,\delta T$$

$\Rightarrow$ *7% increase per 1K warming*
20% increase for 3K

GCMs match observed trend and interannual variations of tropical mean (ocean only) column water vapor when given the observed ocean temperatures as boundary condition



Courtesy of Brian Soden

Local vertically integrated atmospheric moisture budget:

$$P - E = -\nabla \cdot F = -\nabla \cdot (\rho v q)$$

precipitation

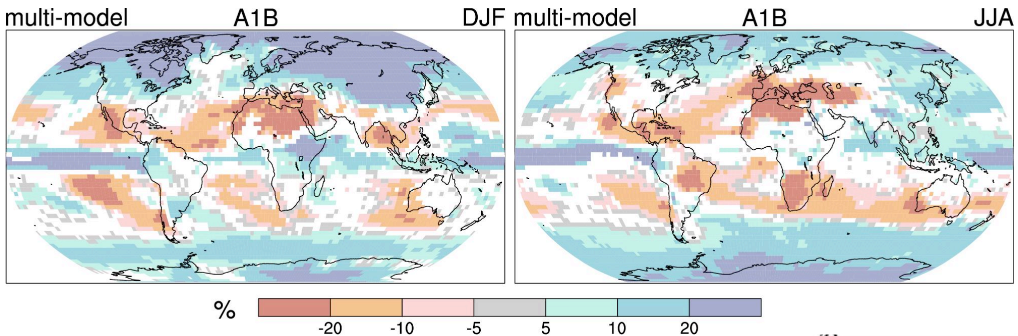
evaporation

vertically integrated moisture flux

vapor mixing ratio

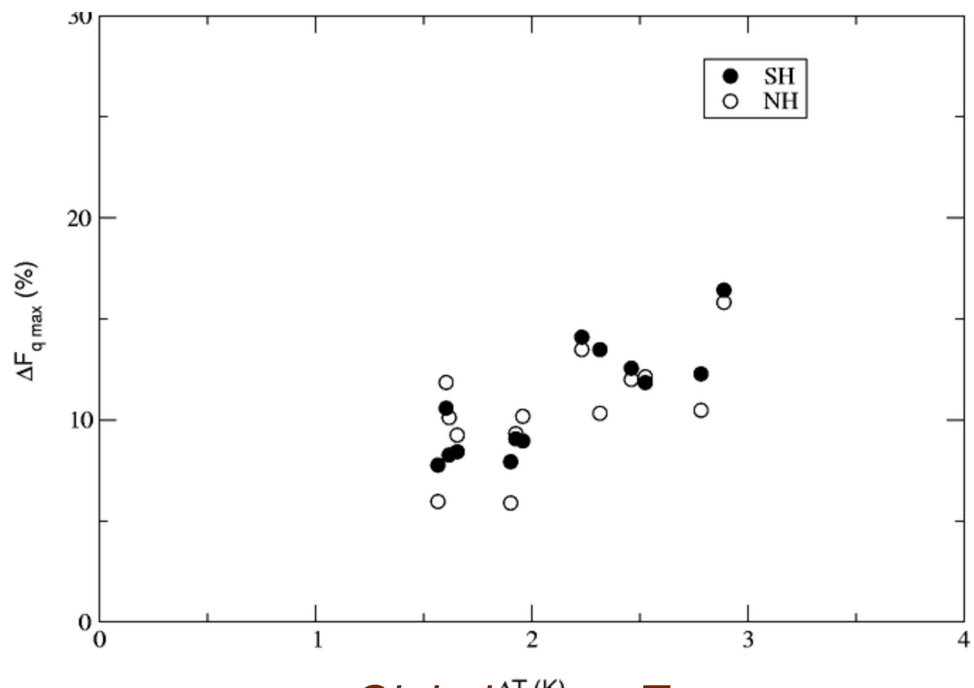
$$\frac{\delta F}{F} \approx \frac{\delta q}{q} \approx 0.07\, \delta T$$

But response of global mean temperature is correlated (across GCMs) with the response of the poleward moisture flux responsible for the pattern of subtropical decrease and subpolar increase in precipitation

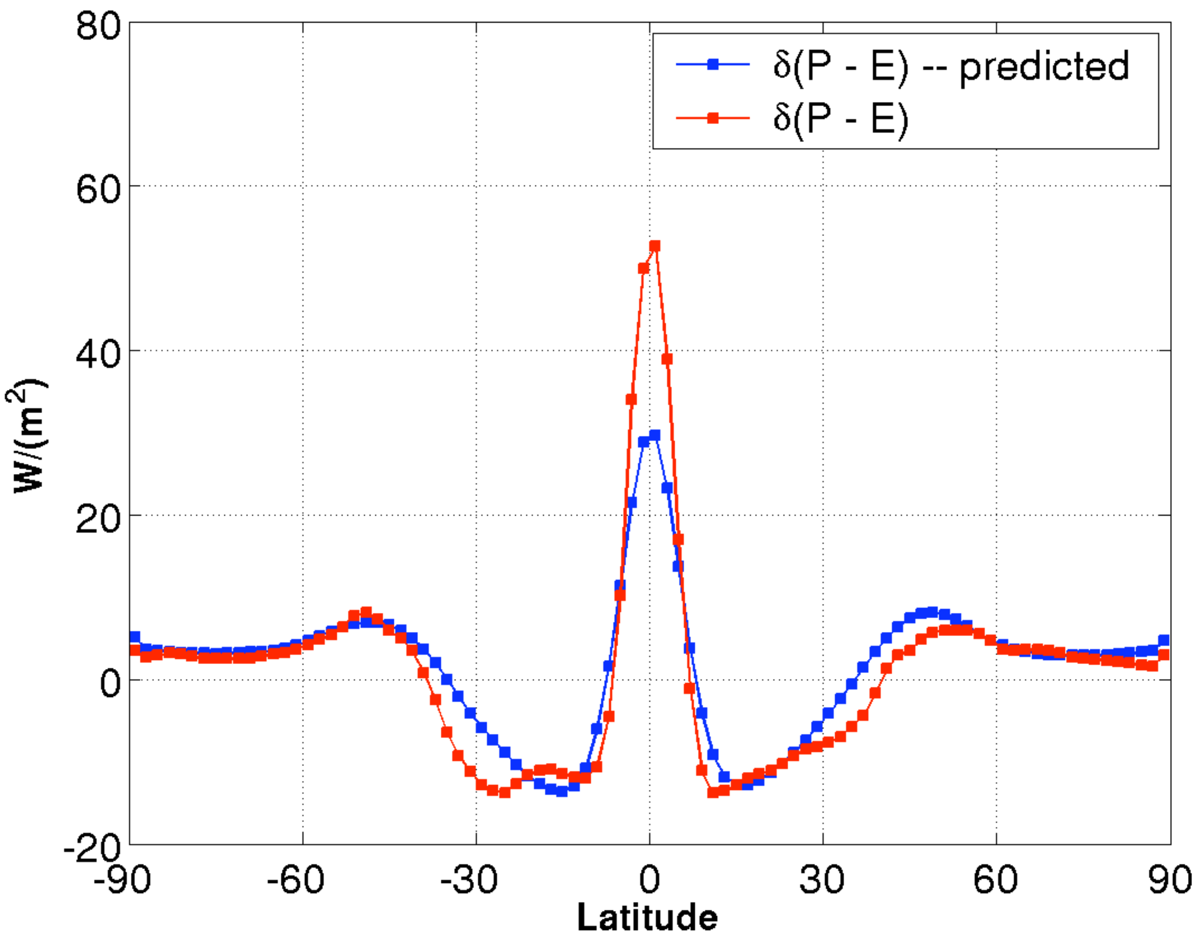


PCMDI/CMIP3

% increase in poleward moisture flux In midlatitudes

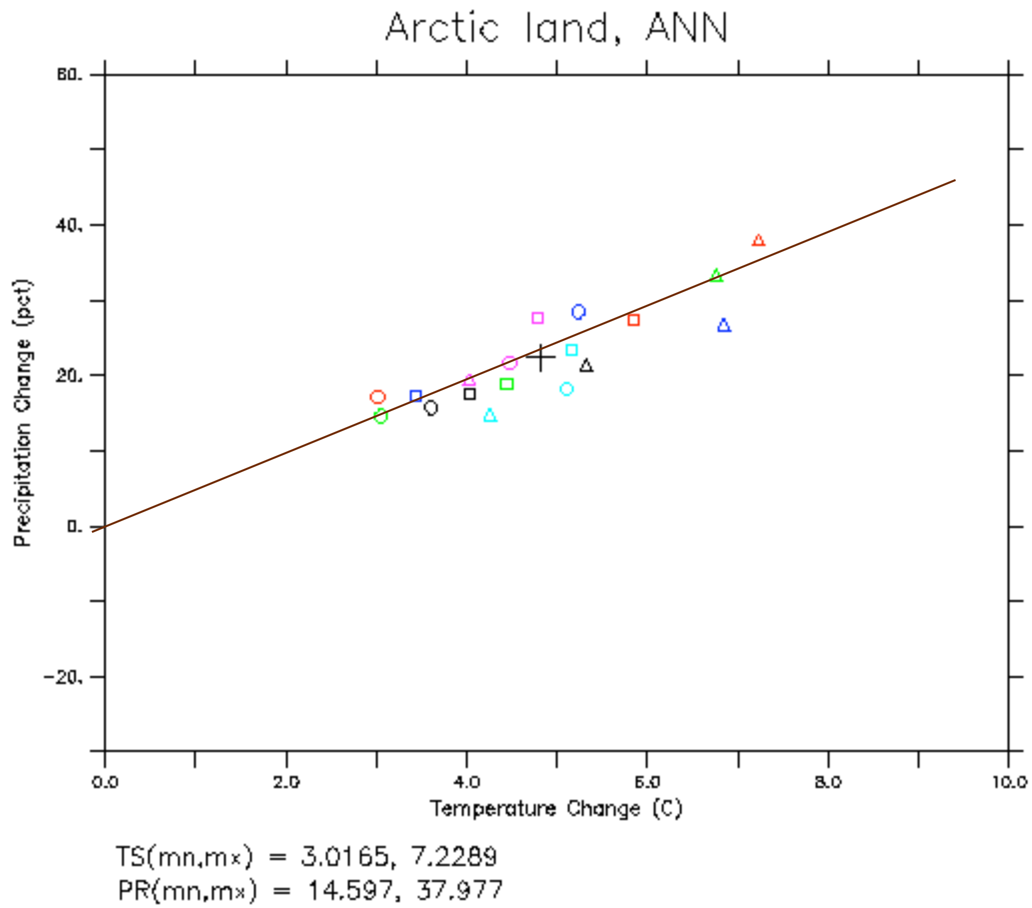


Global mean T



One can see effects of poleward shift of midlatitude circulation
And increase(!) in strength of Hadley cell

PCMDI -AR4 Archive

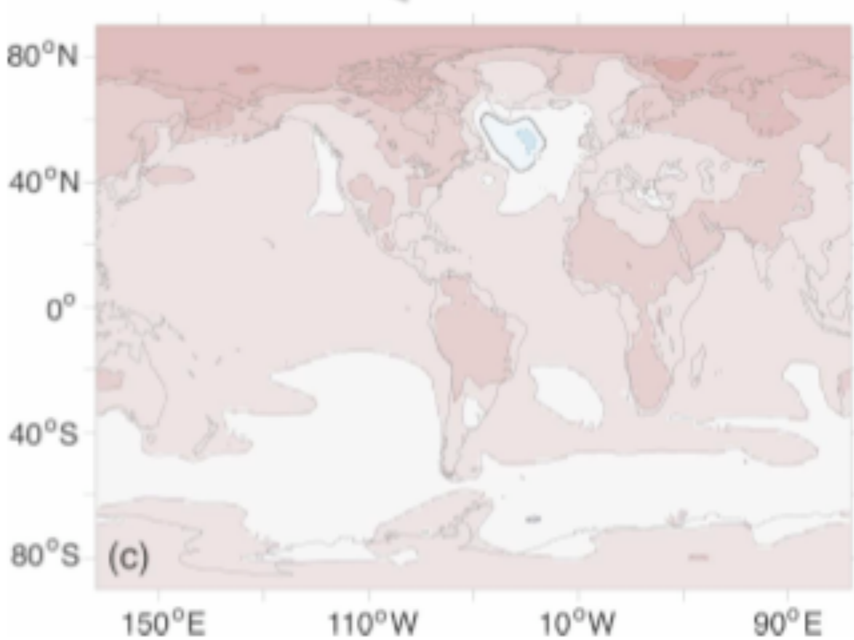


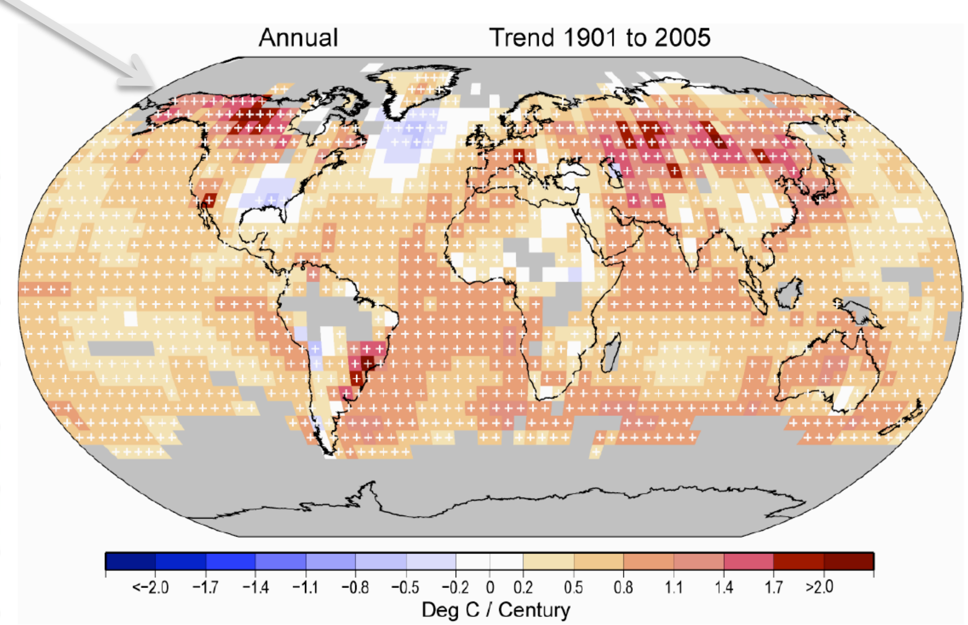
% Precipitation change

Temperature change

One often sees the statement that
"Global mean is useful because averaging reduces noise"

But one can reduce noise a lot more
by projecting temperature change onto a pattern that looks like
this (pattern predicted in response to increase in CO2)
or this (observed linear trend)

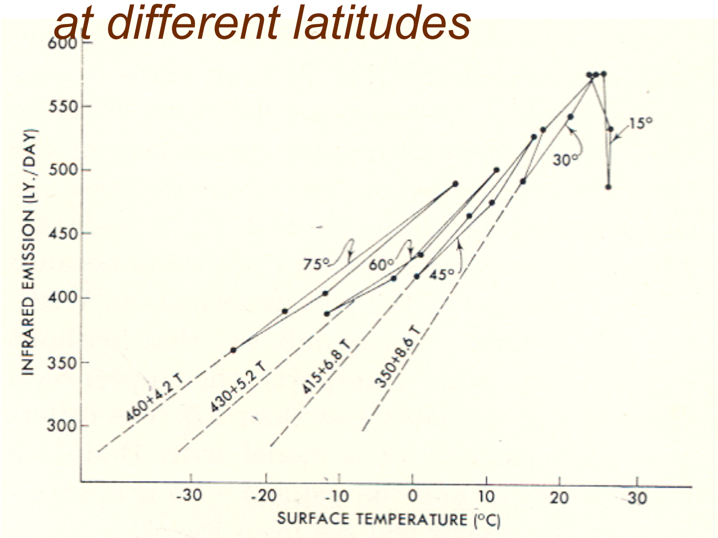




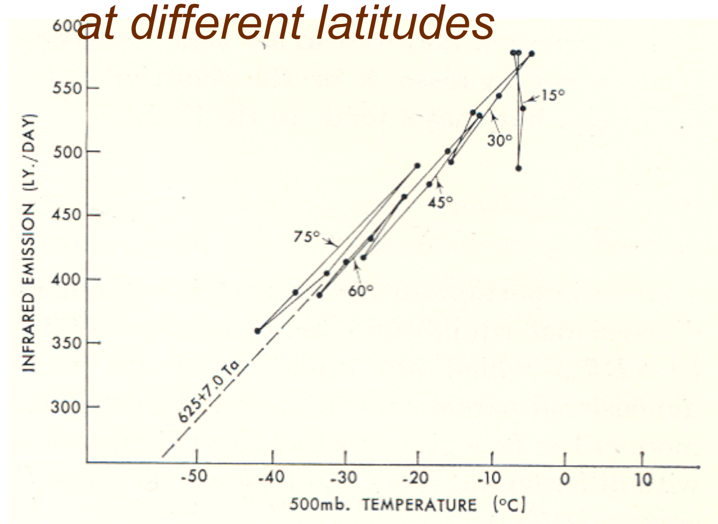
Or one can find the pattern that maximizes the ratio of decadal scale to interannual variability – Schneider and Held 2001

“The global mean surface temperature has an especially simple relationship with the global mean TOA energy balance” ??

Seasonal OLR vs Surface T at different latitudes



Seasonal OLR vs 500mb T at different latitudes



$$F(\theta) = \int \beta(\theta,\xi)\delta T(\xi)d\xi$$ *Most general linear OLR-surfaceT relation*

$$< F > \equiv \int F(\theta)d\theta = \int B(\xi)T(\xi)d\xi; \qquad B(\xi) = \int \beta(\theta,\xi)d\theta$$

$$if \quad \delta T(\theta) = f(\theta) < T > \quad then \quad < F >= \tilde{B} < T >$$

$$\tilde{B} \equiv \int B(\xi) f(\xi) d\xi$$

Relation between global means depends on spatial structure

Efficacy (Hansen et al, 2005) :

Different sources of radiative forcing that provide the same net global flux at the top-of-atmosphere can give different global mean surface temperature responses

Forcing for doubling CO_2 roughly 3.7 W/m^2

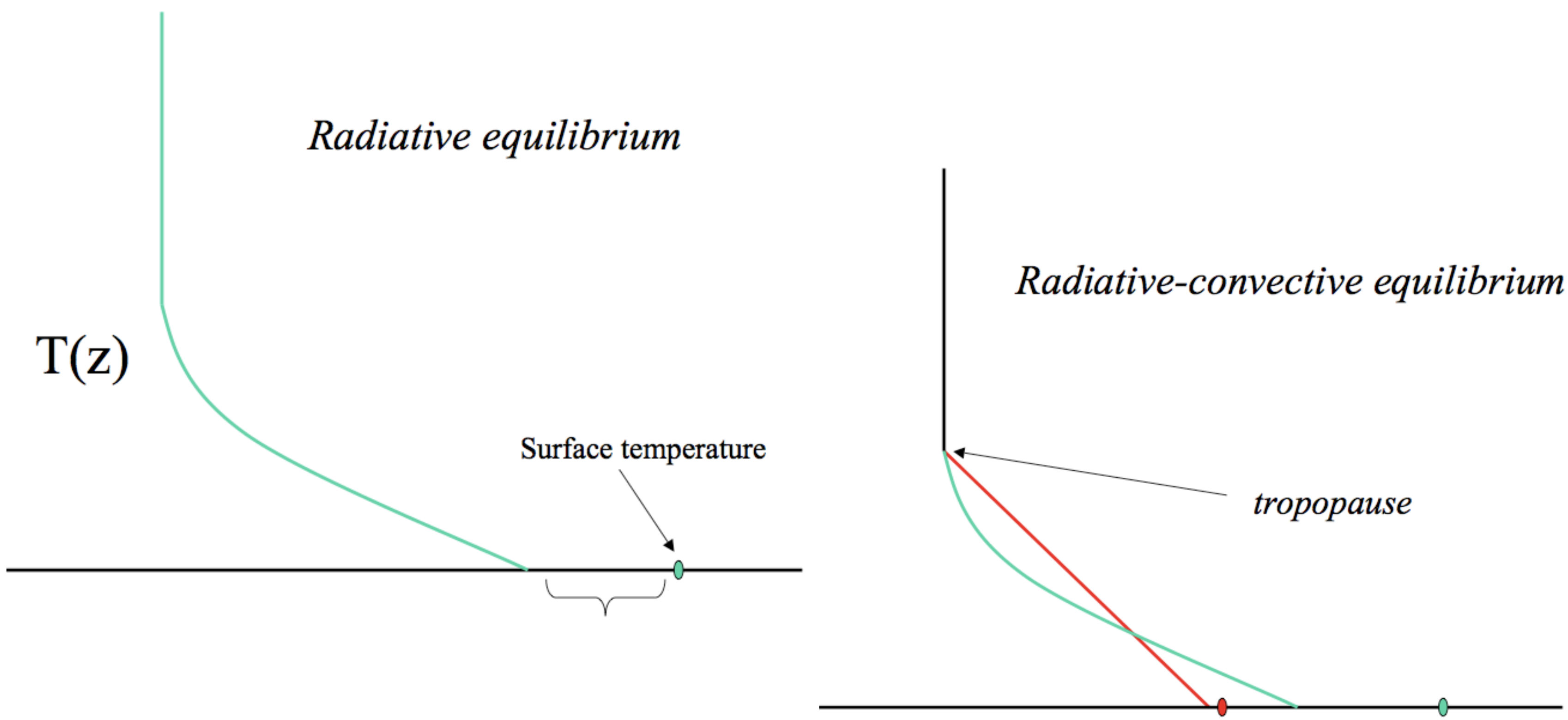
If global mean response to doubling CO_2 is T_{2X}

E = efficacy = $(<T> / T_{2X})(3.7/F)$

One explanation for efficacy:
Responses to different forcings have different spatial structures
Tropically dominated responses => E <1
Polar dominated responses => E>1

Why focus on top of atmosphere energy budget rather than surface?

Because surface is strongly coupled to atmosphere by non-radiative fluxes (particularly evaporation)



Classic example: adding absorbing aerosol does not change T, but reduces evaporation

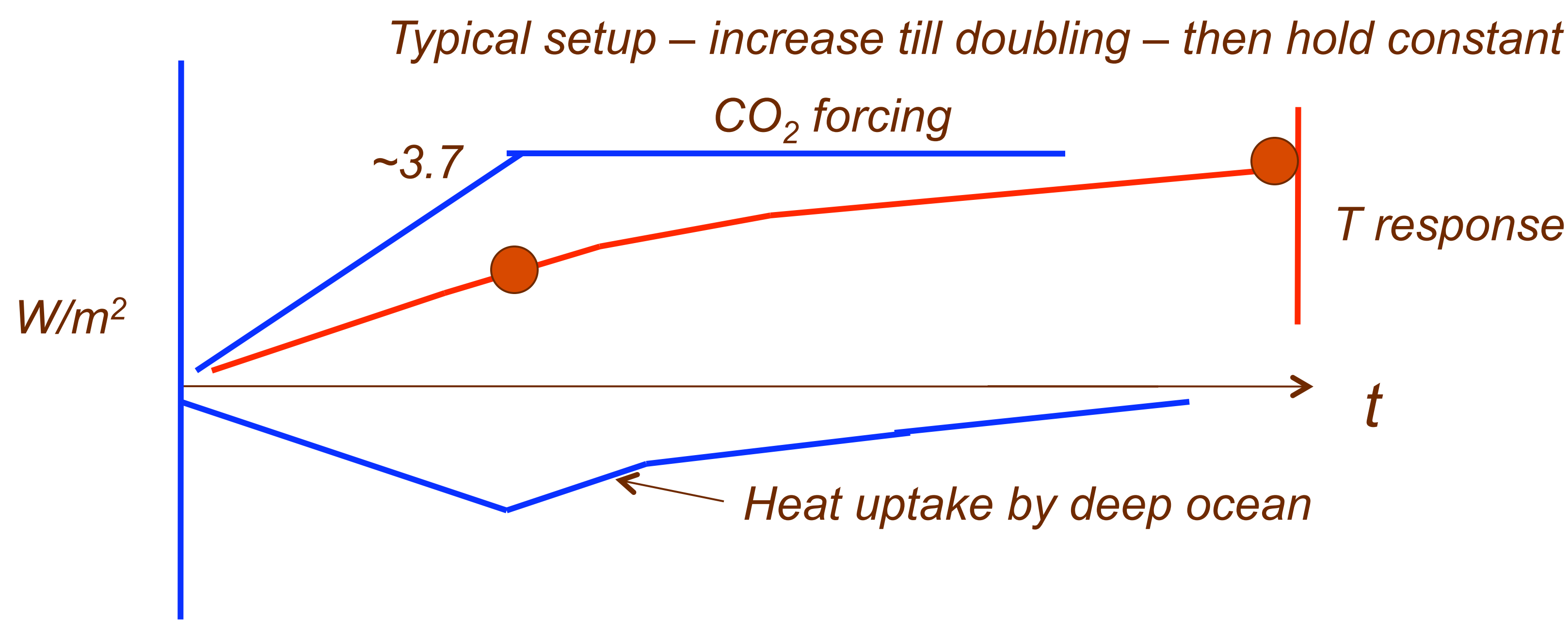
If net solar flux does not change, outgoing IR does not change either (in equilibrium),
-- with increased CO2, atmosphere is more opaque to infrared photons
=> average level of emission to space moves upwards, maintaining same T
=> warming of surface, given the lapse rate

Final response depends on how other absorbers/reflectors
(esp. clouds, water vapor, surface snow and ice)
change in response to warming due to CO_2,
and on how the mean lapse rate changes

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

But what is the "system"?
glaciers? "natural" vegetation?
Why not specify emissions rather than concentrations?

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



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

“Observational constraints” on climate sensitivity (equilibrium or transient)

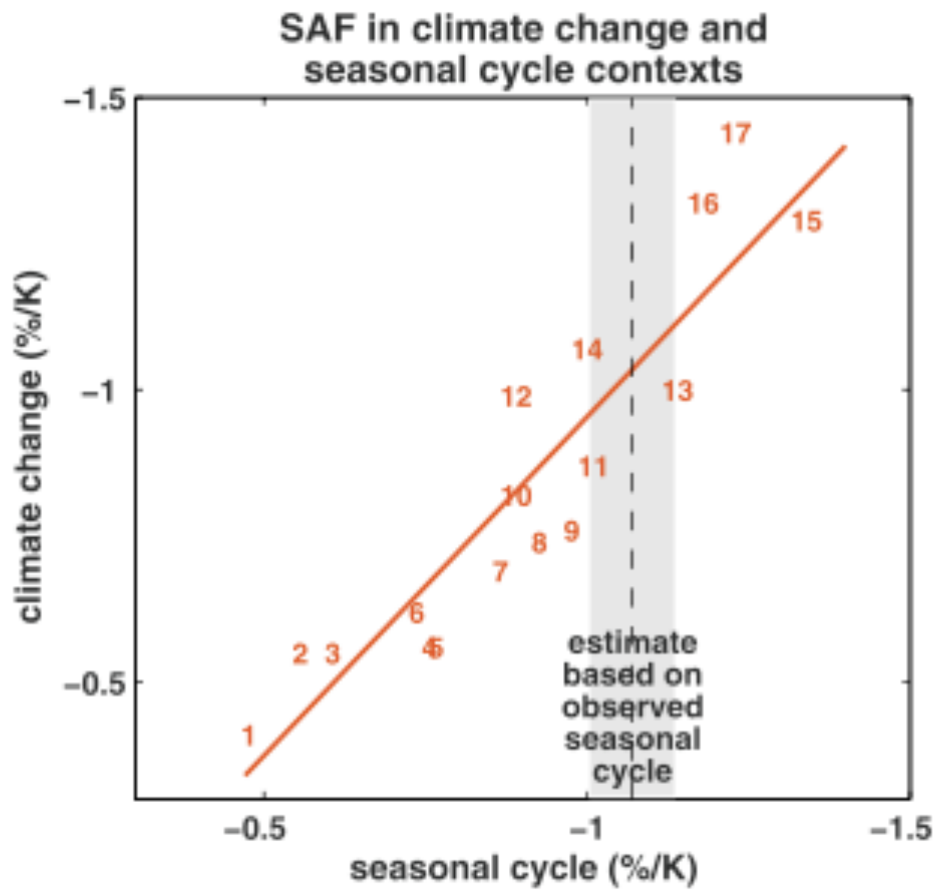
Simulates some observed phenomenon:
comparison with simulation constrains a,b,c …

Model (a,b,c,…)

predicts climate sensitivity;
depends on a,b,c,…

Model can be GCM – in which case constraint can be rather indirect
(constraining processes of special relevance to climate sensitivity)
Or it can be simple model in which climate sensitivity
is determined by 1 or 2 parameters.

A great example of an observational constraint: looking across GCMs, strength of snow albedo feedback very well correlated with magnitude of mean seasonal cycle of surface albedos over land
=> observations of seasonal cycle constrain strength of feedback



Hall and Xu, 2006

Can we do this for cloud feedbacks?

The simplest linear model

forcing

Heat uptake

$$C\frac{dT}{dt} = F - \beta T \equiv N$$

$$T_{EQ} = F/\beta$$

The left-hand side of this equation (the ocean model) is easy to criticize, but what about the right hand side?

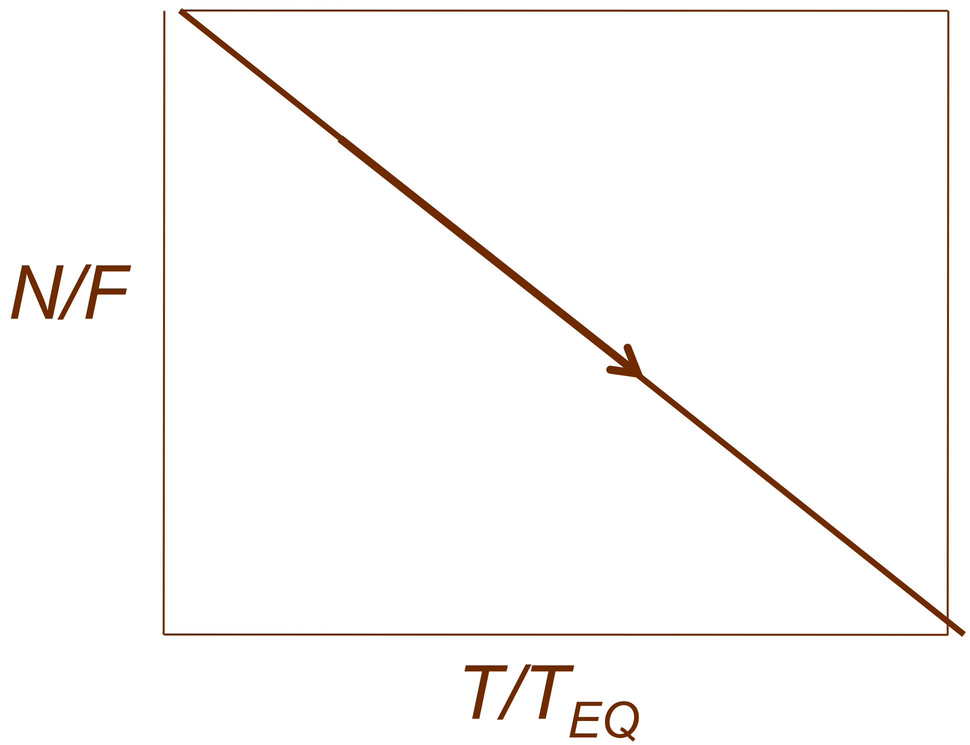
The simplest linear model

$$C\frac{dT}{dt} = F - \beta T \equiv N$$

$$T_{EQ} = F/\beta$$

$$N/F = 1 - T/T_{EQ}$$

If correct, evolution should be along the diagonal

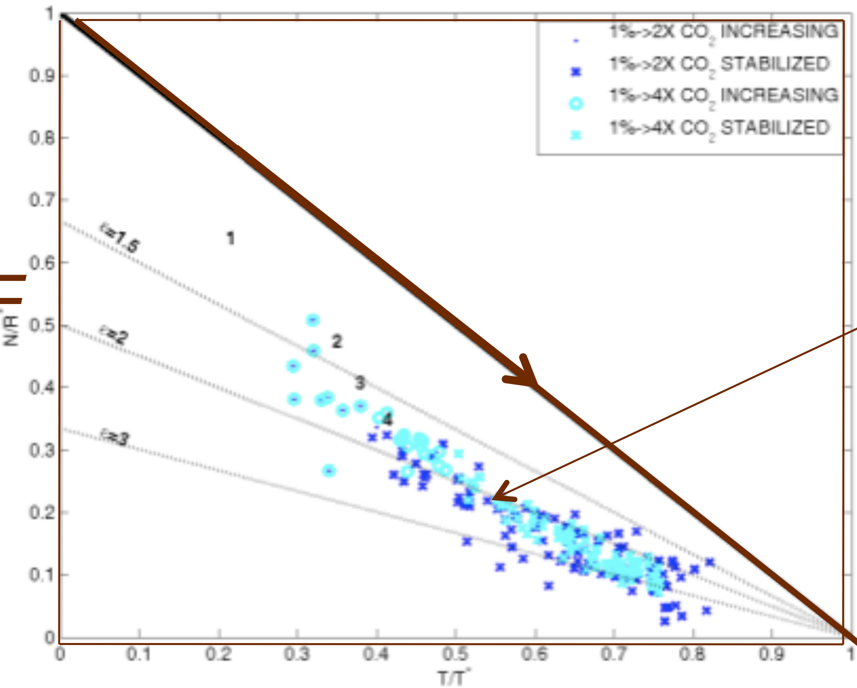


$$C\frac{dT}{dt} = F - \beta T \equiv N$$

$$T_{EQ} = F/\beta$$

$$N/F = 1 - T/T_{EQ}$$

N/F



T/T_{EQ}

Evolution in a particular GCM (GFDL's CM2.1) for 1/% till doubling + stabilization

$$C\frac{dT}{dt} = F - \beta T \equiv N$$

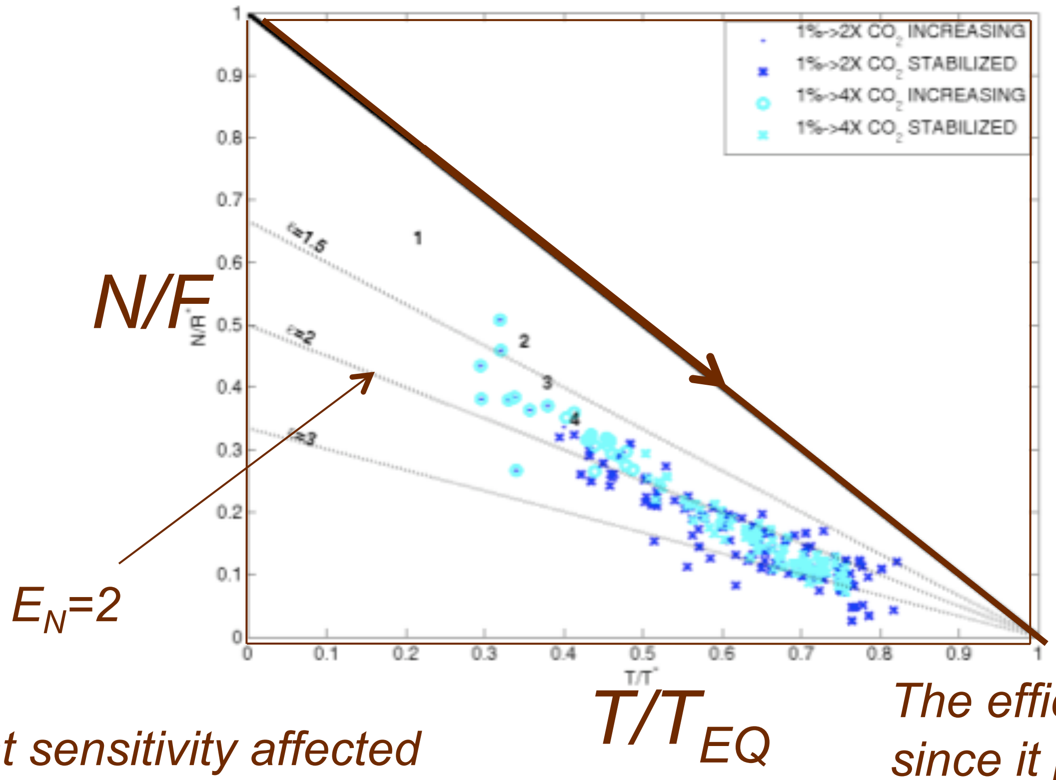
$$T_{EQ} = F/\beta$$

$$N/F = 1 - T/T_{EQ}$$

$$\beta T = F - N$$

replaced by

$$\beta T = F - E_N N$$

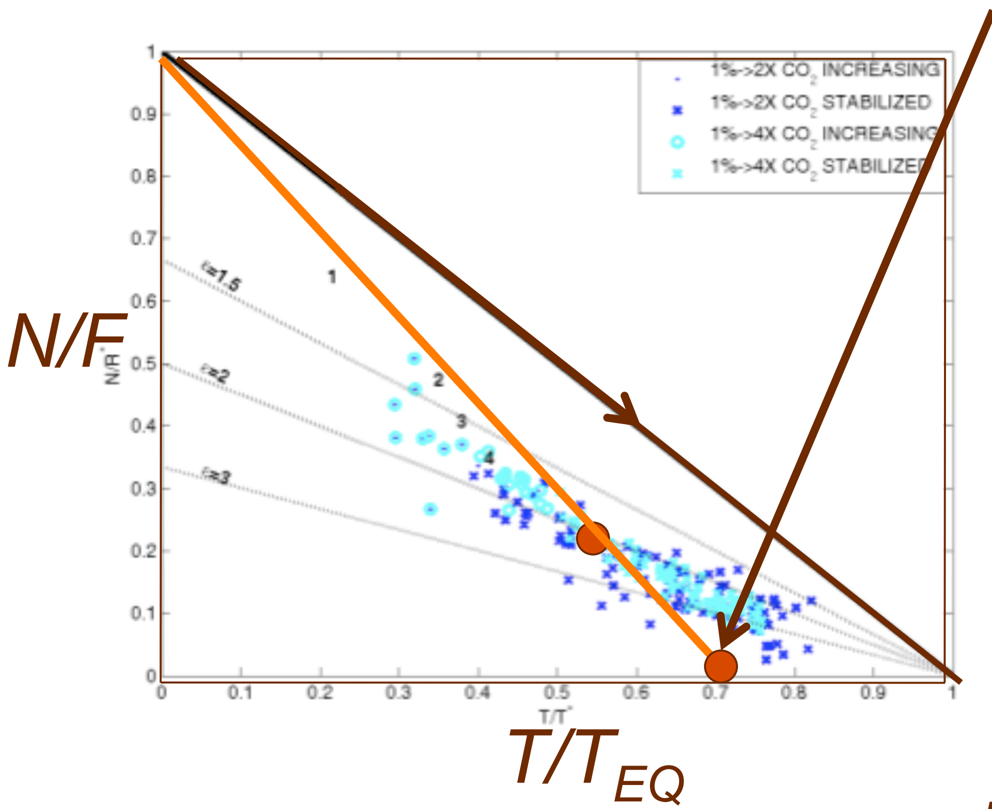


Transient sensitivity affected by efficacy as well as magnitude of heat uptake

The efficacy of heat uptake >1 since it primarily affects subpolar latitudes

Are some of our difficulties in relating different observational constraints on sensitivity due to inadequate simple models/concepts?

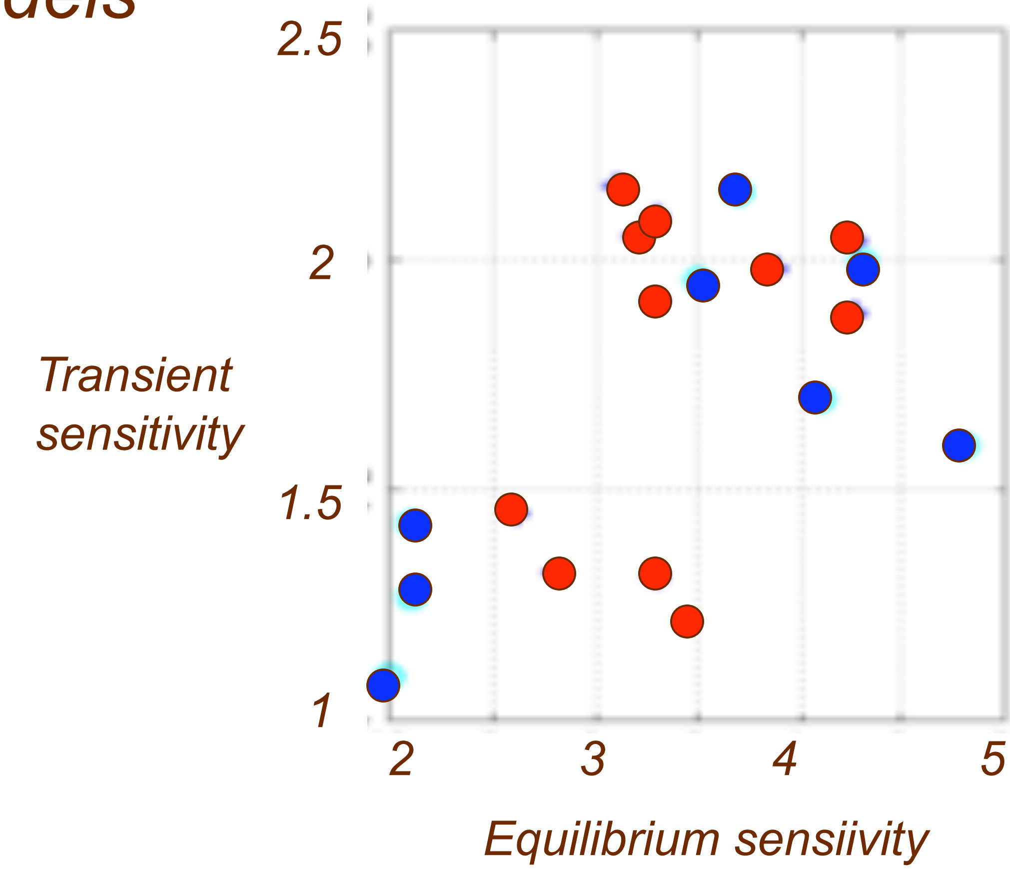
Lots of papers, and IPCC, use concept of "Effective climate sensitivity" to estimate equilibrium sensitivity -- can't integrate models long enough to get to accurate new equilibrium,



Linearly extrapolating from zero, through time of doubling, to estimate equilibrium sensitivity

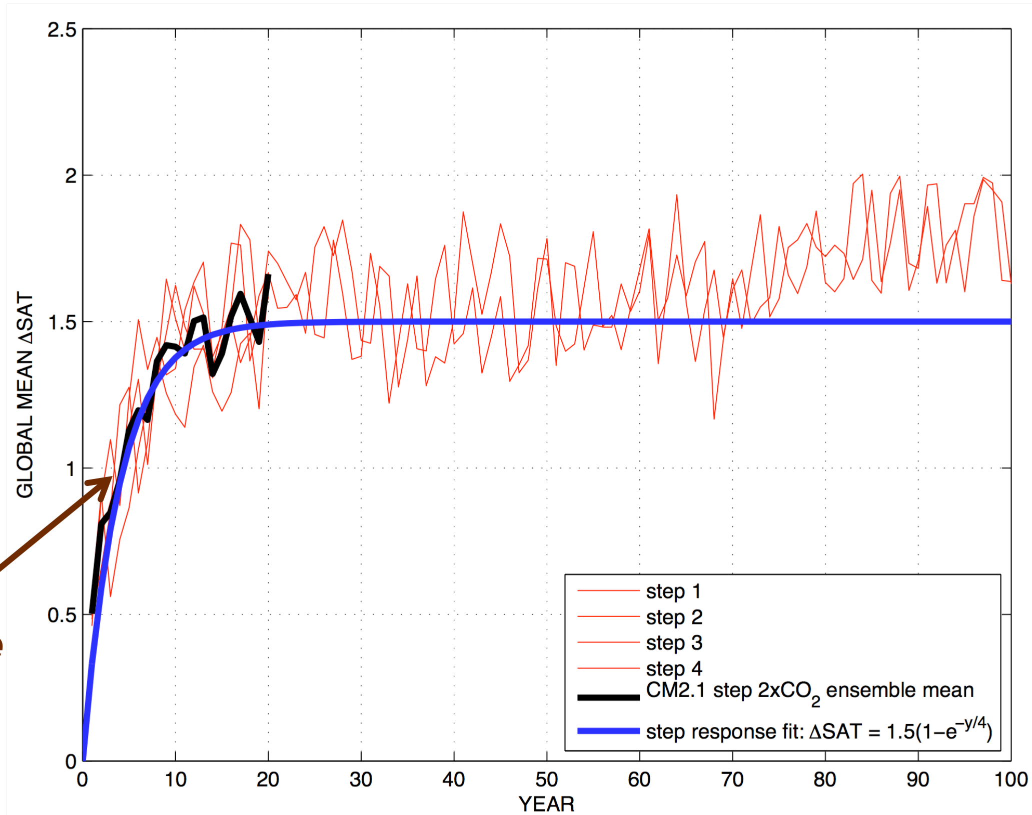
Result is time-dependent

AR4 models



Not well correlated across models – equiilbrium response brings into play feedbacks/dynamics in subpolar oceans that are surpressed in transient response

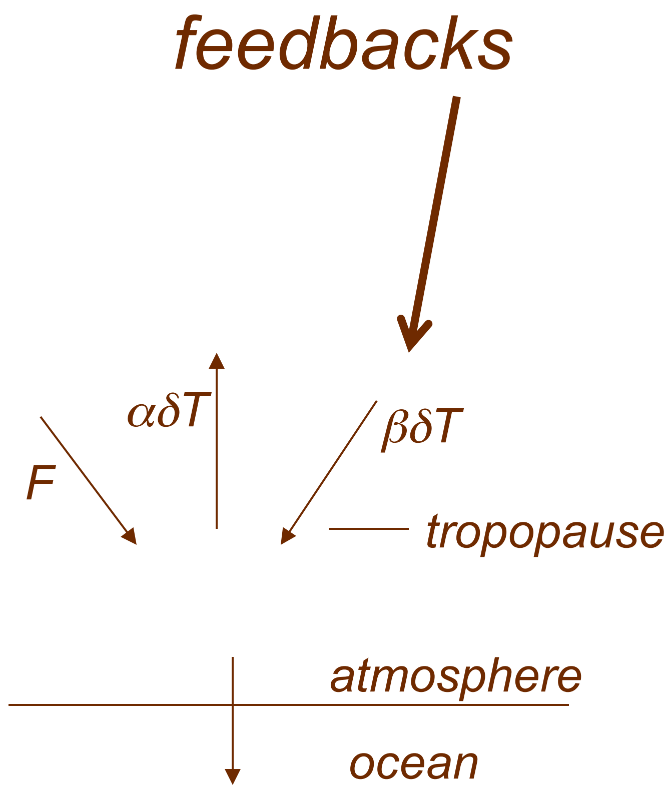
Response of global mean temperature in CM2.1 to instantaneous doubling of CO2
Equilibrium sensitivity >3K
Transient response ~1.6K



Slow response evident only after ~100 yrs and seems irrelevant for transient sensitivity

Fast response

$$T = (1.6K)e^{-t/(4\,yrs)}$$



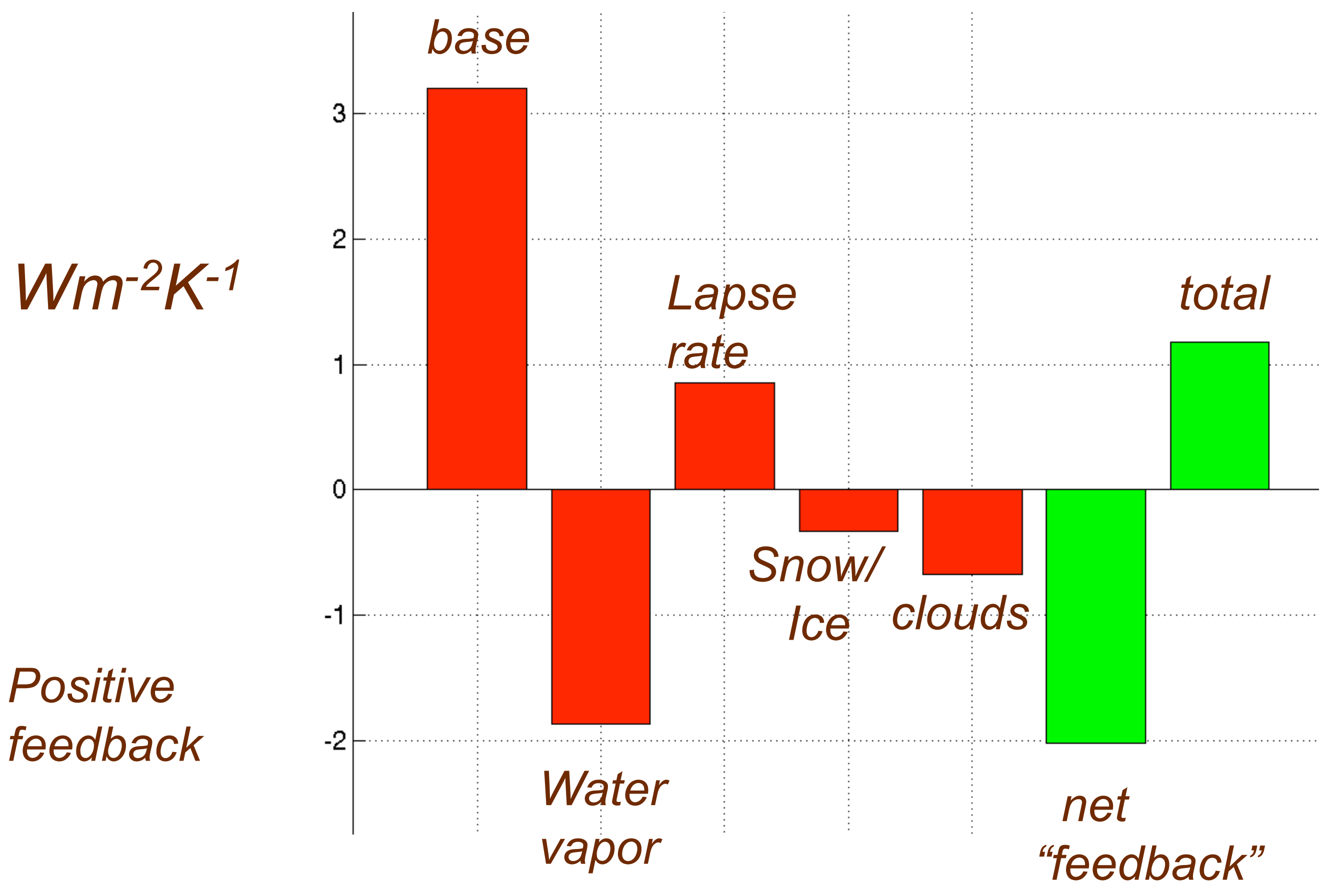
In equilibrium:

$$F = \alpha\delta T = \gamma\delta T - \beta\delta T$$

$$F + \beta\delta T = \gamma\delta T$$

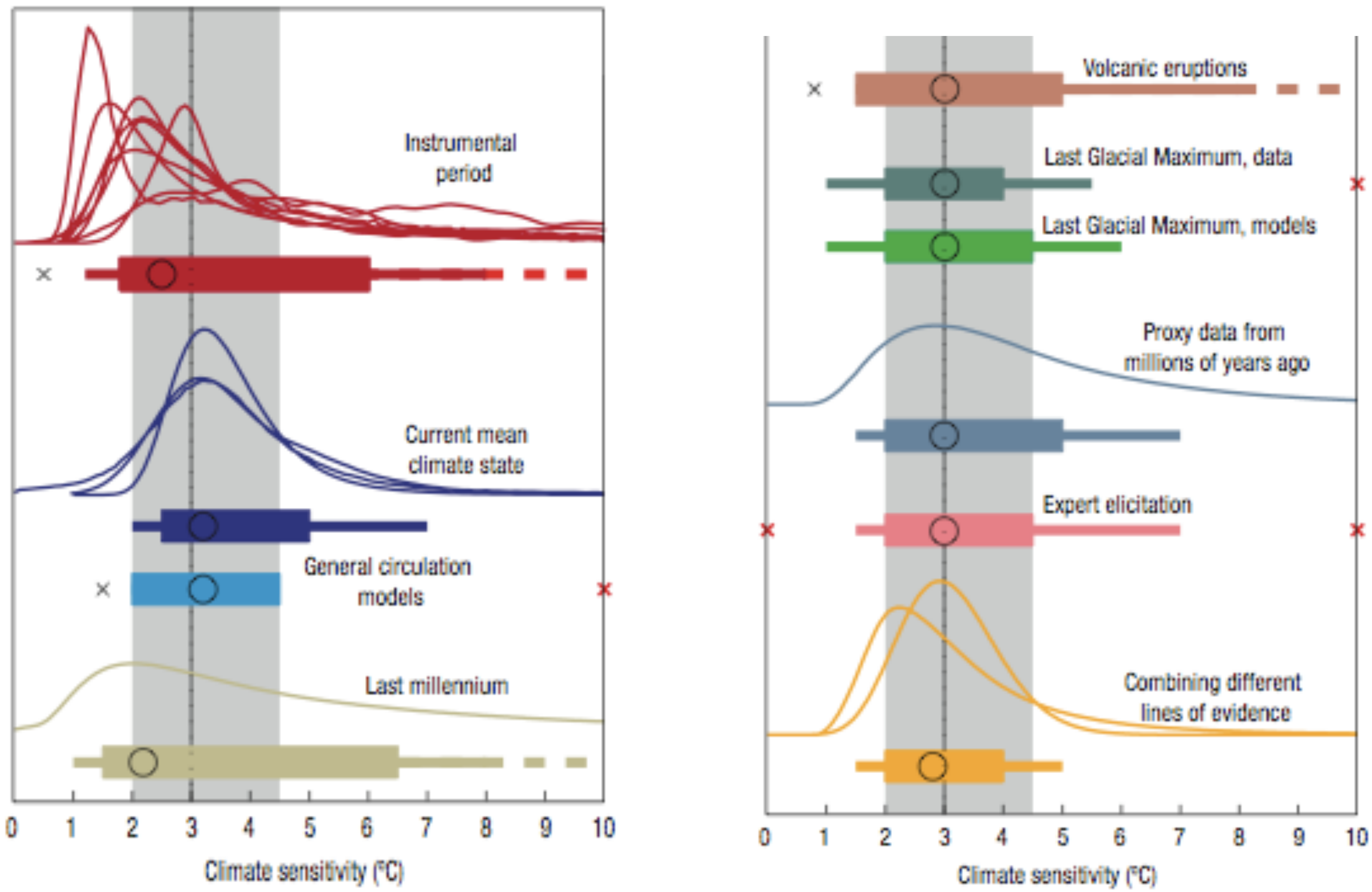
$$\delta T = \frac{F}{\alpha} = \frac{F}{\gamma - \beta} = \frac{F}{\gamma}\left(\frac{1}{1-f}\right)$$

Global mean feedback analysis for CM2.1 (in A1B scenario over 21st century)

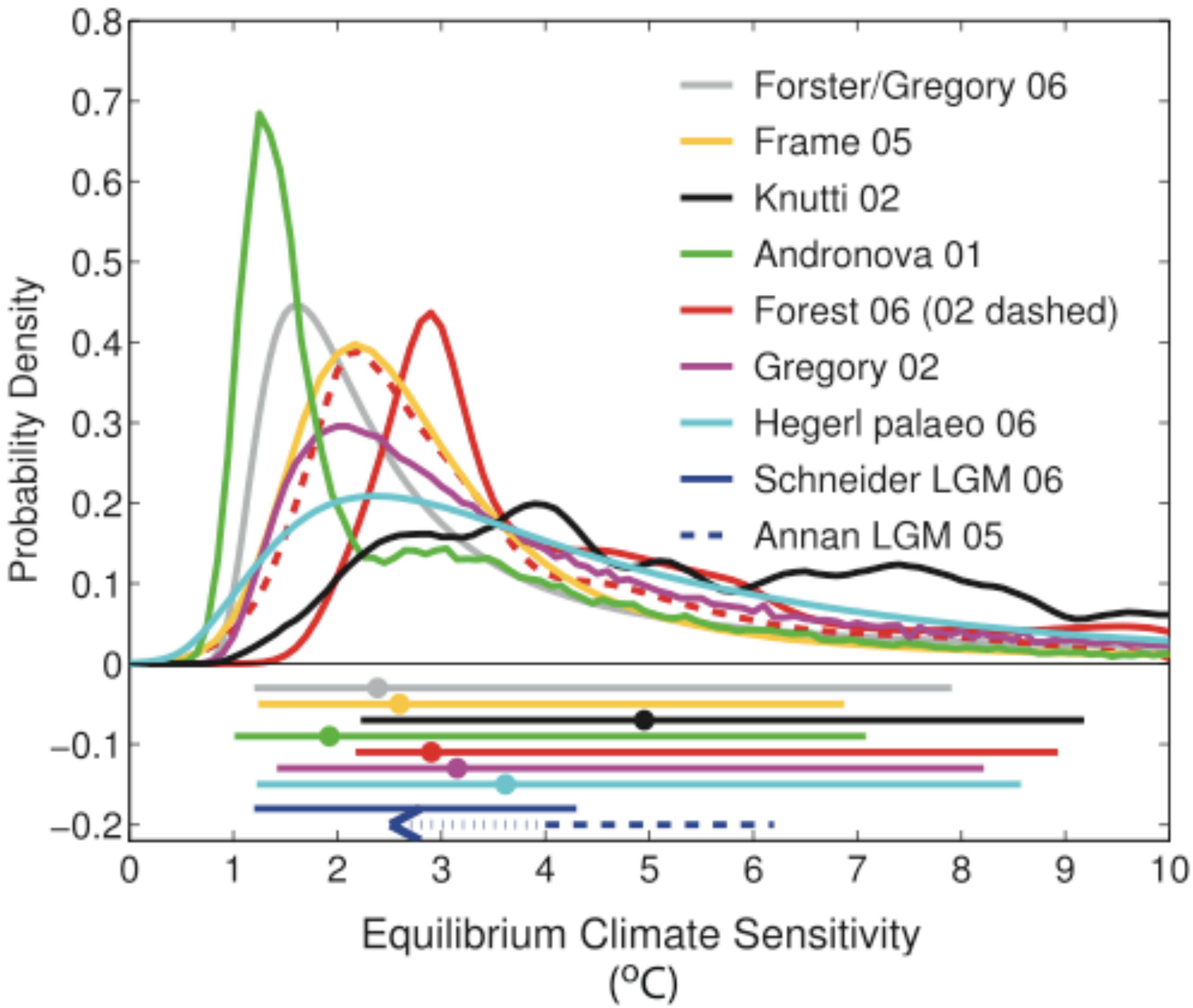


Base in isolation would give sensitivity of ~1.2K
Feedbacks convert this to ~3K

Assorted estimates of equilibrium sensitivity

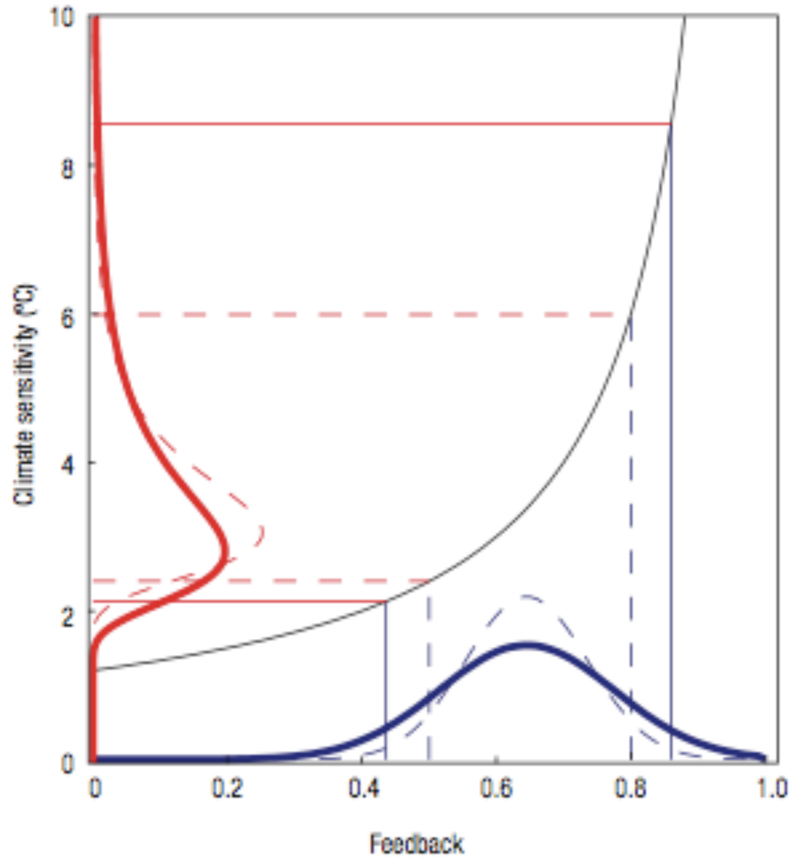


Knutti+Hegerl, 2008



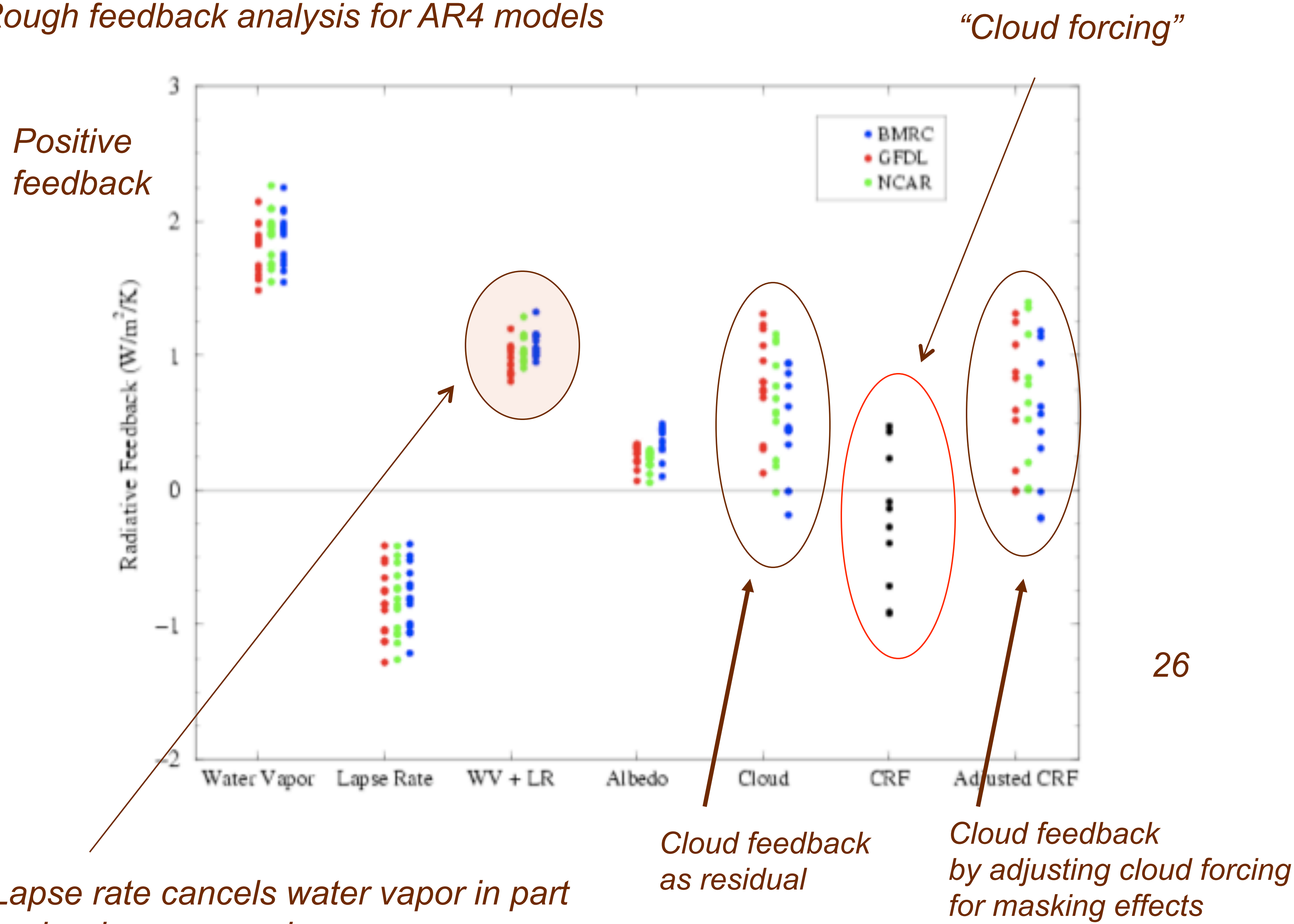
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
Probability Density
Forster/Gregory 06
Frame 05
Knutti 02
Andronova 01
Forest 06 (02 dashed)
Gregory 02
Hegerl palaeo 06
Schneider LGM 06
Annan LGM 05
0 1 2 3 4 5 6 7 8 9 10
Equilibrium Climate Sensitivity
(°C)

Gaussian distribution of f => skewed distribution of 1/(1-f)



Roe-Baker

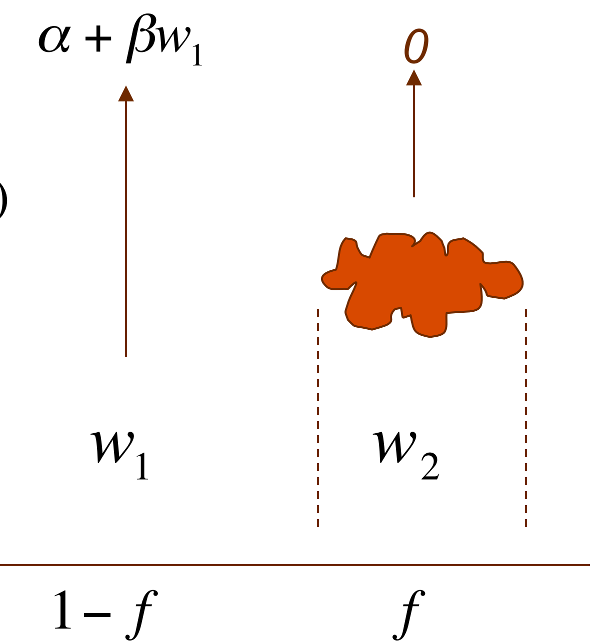
Rough feedback analysis for AR4 models



Lapse rate cancels water vapor in part and reduces spread

Cloud feedback is different from change in cloud forcing

$$\overline{R} = (1 - f)(\alpha + \beta w_1)$$



$$\delta\overline{R} = \delta_C\overline{R} + \delta_W\overline{R}$$

Cloud feedback $\delta_C\overline{R} = -(\alpha + \beta w_1)\delta f$

Water vapor feedback $\delta_W\overline{R} = (1 - f)\beta\delta w_1$

Cloud forcing

$$C_{RF} = -f(\alpha + \beta w_2)$$

$$\delta C_{RF} = -(\alpha + \beta w_2)\delta f - f\beta\delta w_2$$

Another problem

A = control   *B = perturbation* $\delta \sim B - A$

1) *Simple substitution*

but taking clouds from A and water vapor from B decorrelates them

$$\overline{R(w_B, c_A)} = (1 - f_A)\left[\alpha + \beta\left(f_B w_{2B} + (1 - f_B) w_{1B}\right)\right]$$

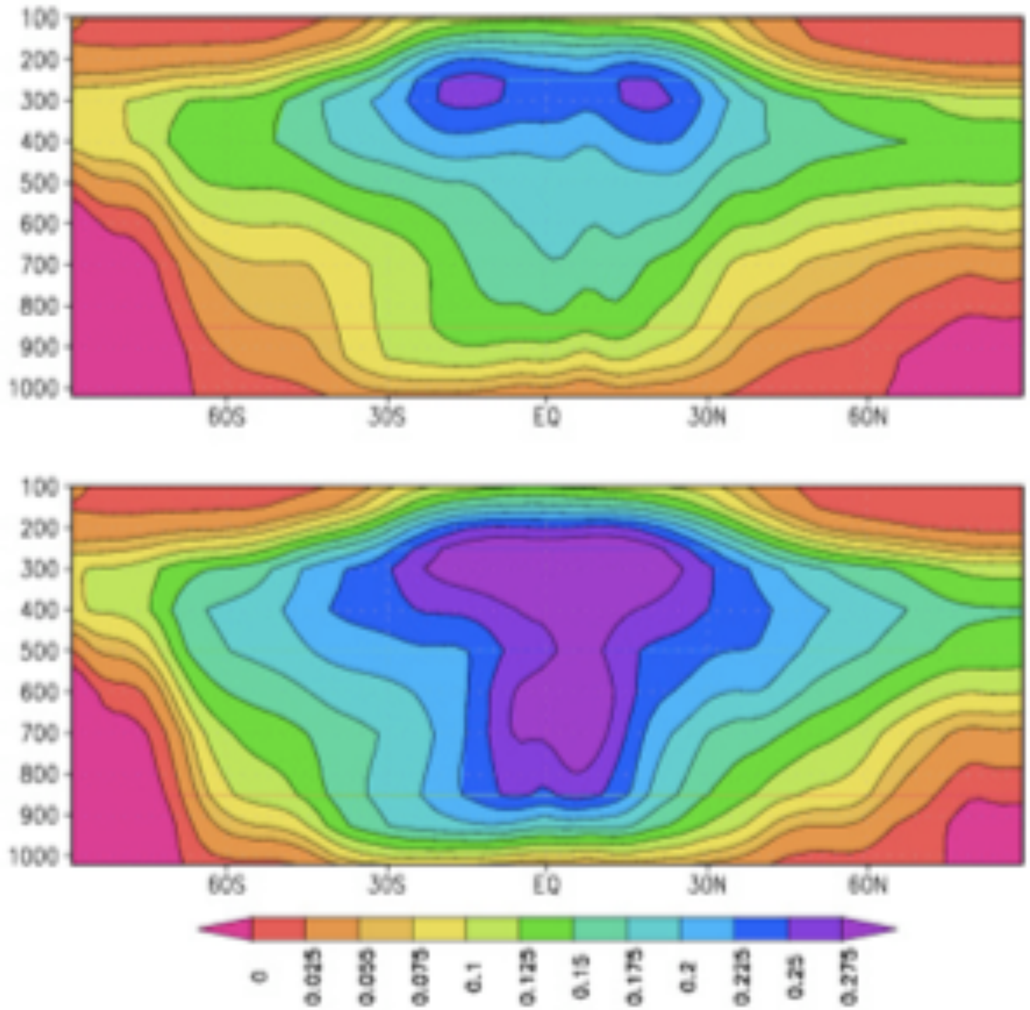
$$\delta_W \overline{R} \approx \overline{R(w_B, c_A)} - \overline{R(w_A, c_A)} = \beta(1 - f)\delta w_1 + \beta(1 - f) f (w_2 - w_1)$$

Soden et al, J.Clim, 2008
describe alternative ways of
Alleviating this problem

Right answer   *Not a perturbation quantity*

Annual, zonal mean water vapor kernel, normalized to correspond to % change in RH

Mostly comes from upper tropical troposphere, so negatively correlated with lapse rate feedback



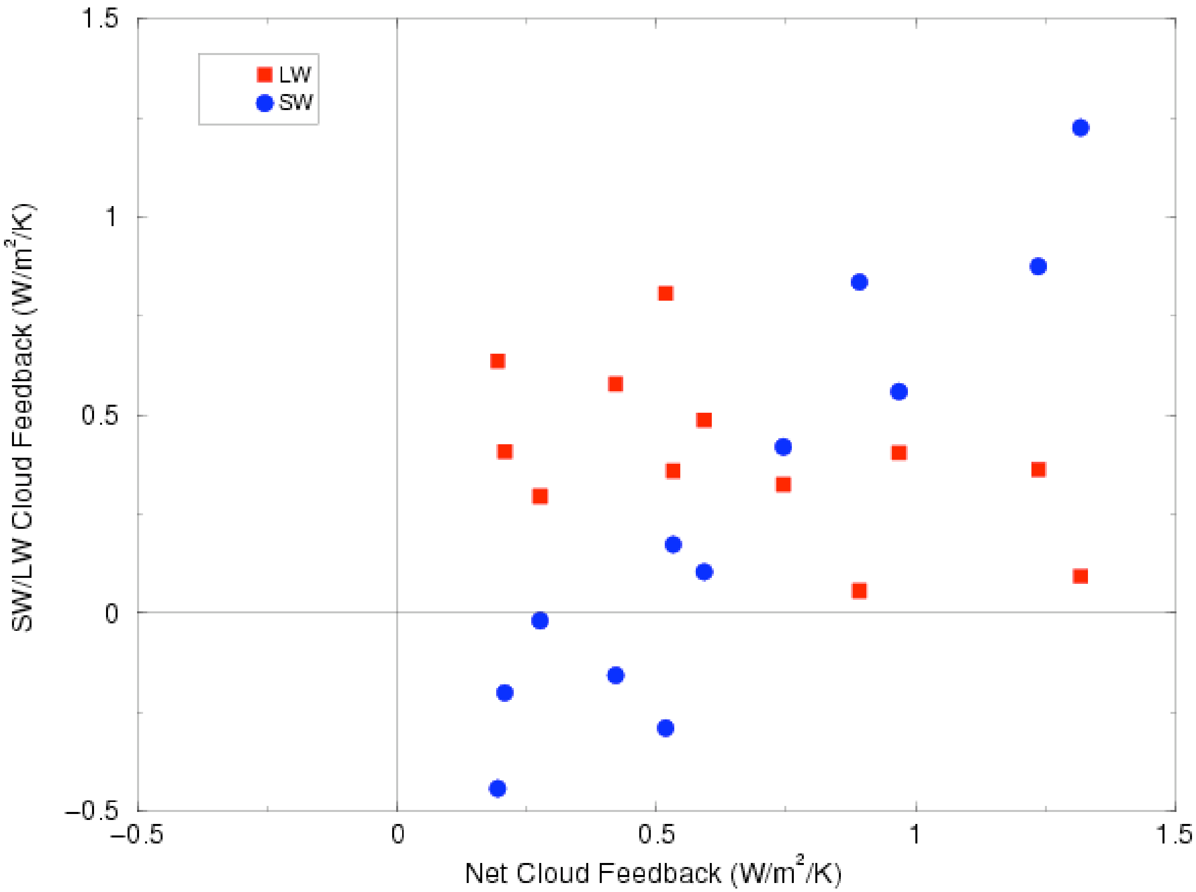
Total

Clear sky

Difference between total and clear sky kernels used to adjust for masking effects and compute cloud feedback from change in cloud forcing

LW feedbacks positive (FAT hypothesis? => Dennis's lecture)
SW feedbacks positive/negative, and correlated with total

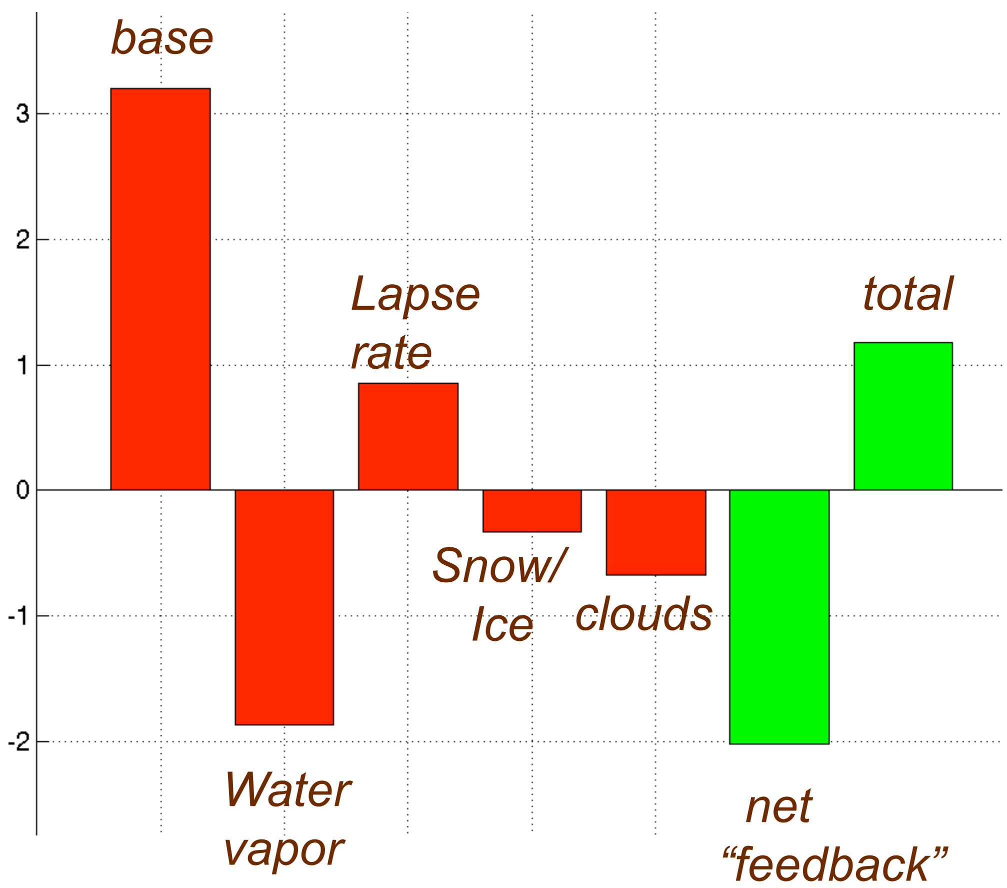
SW and LW cloud feedback



Net cloud feedback from 1%/ yr CMIP3/AR4 simulations

Courtesy of B. Soden

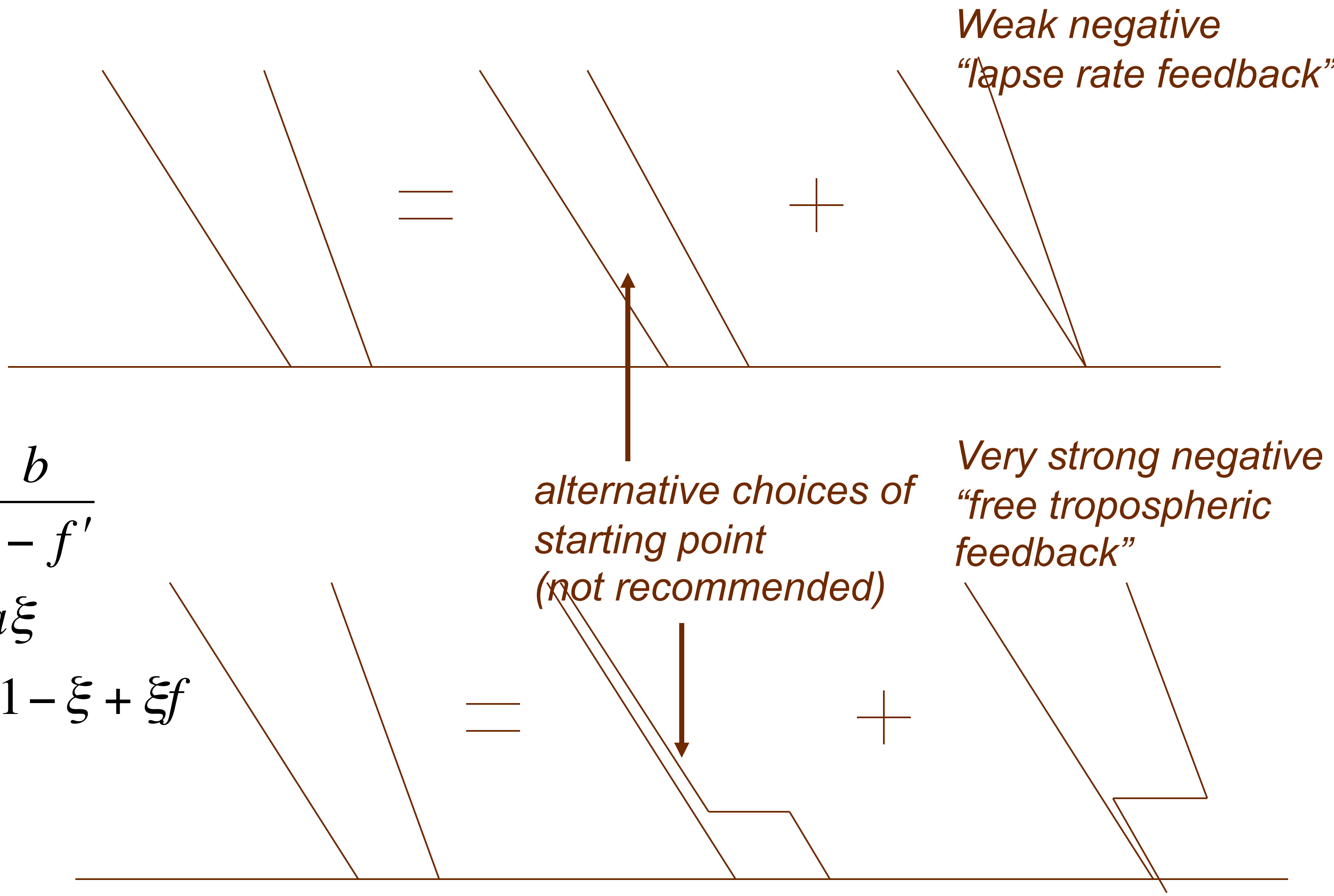
$Wm^{-2}K^{-1}$


base
Water vapor
Lapse rate
Snow/ Ice
clouds
net "feedback"
total
3
2
1
0
-1
-2

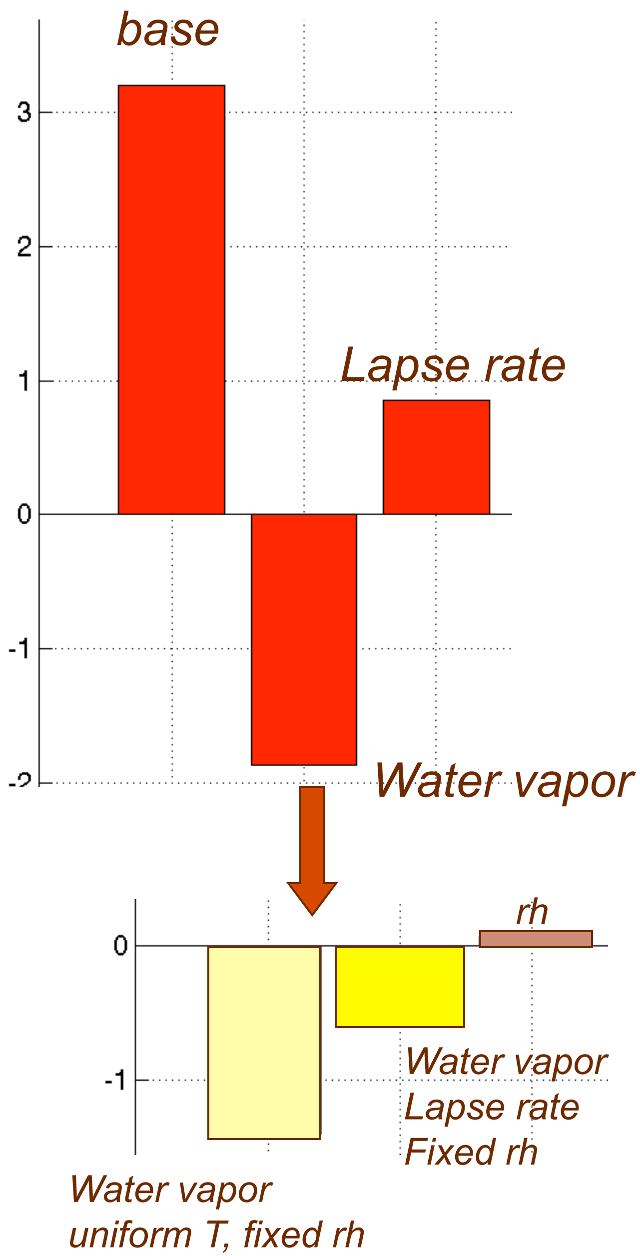
$$\frac{a}{1-f} = \frac{b}{1-f'}$$

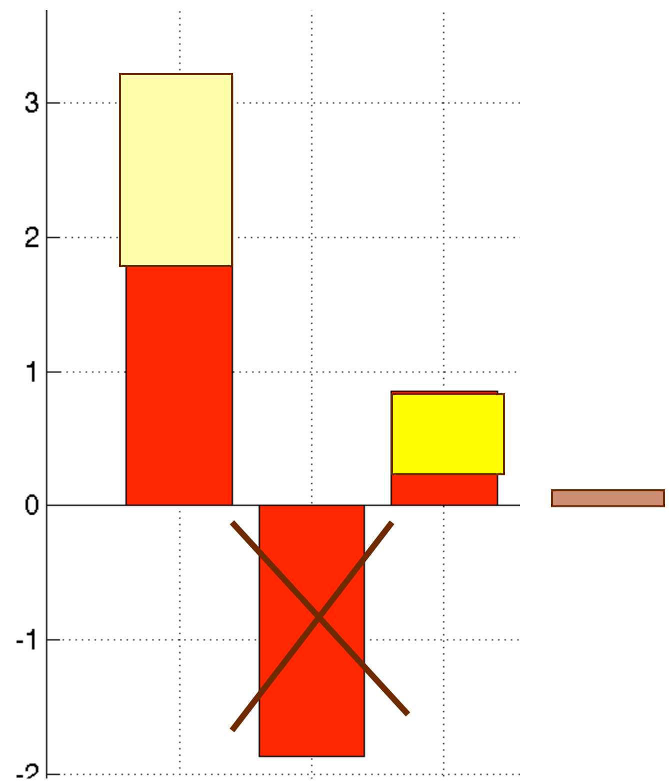
$$b = a\xi$$

$$f' = 1 - \xi + \xi f$$



Choice of “base” = “no feedback” is arbitrary!





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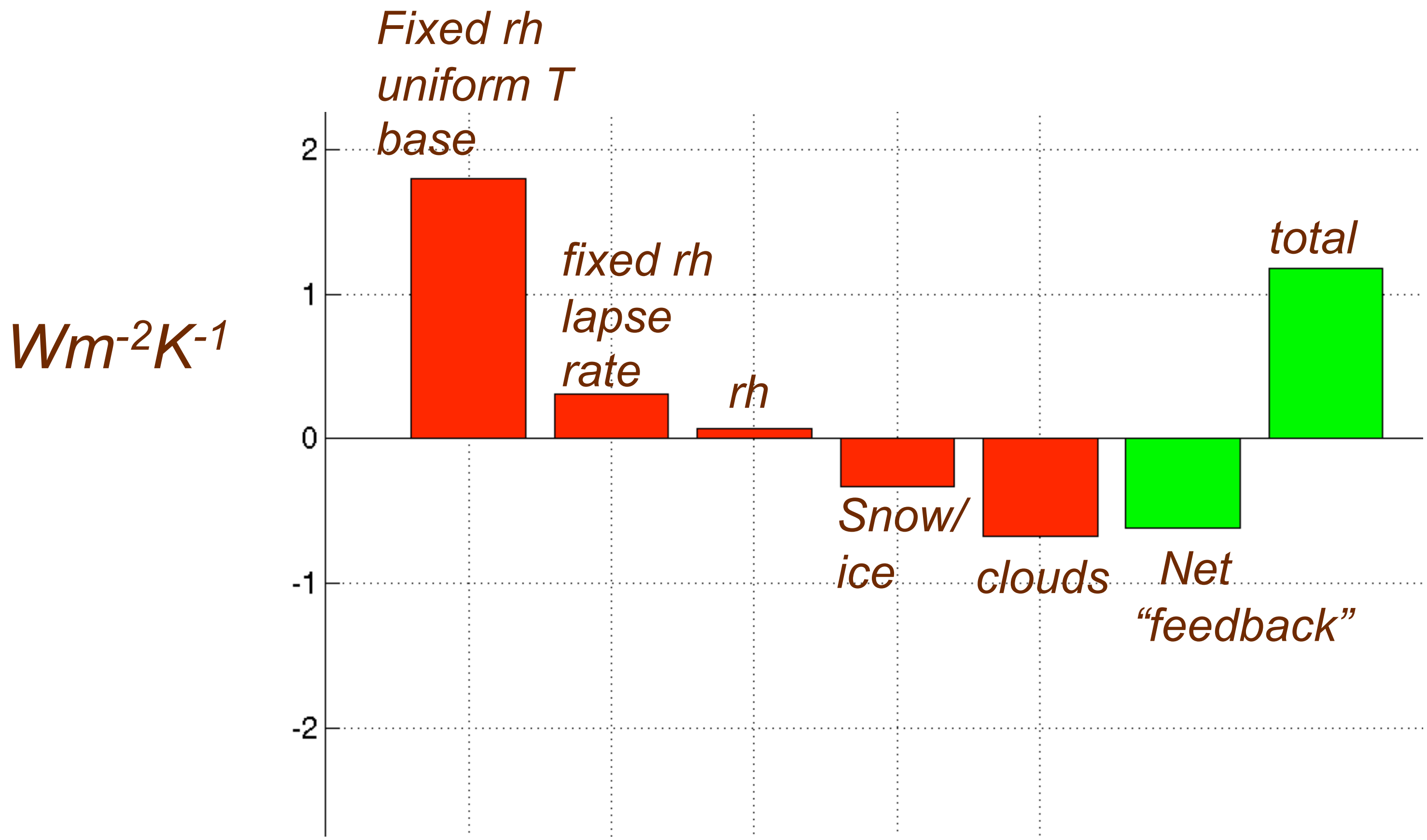
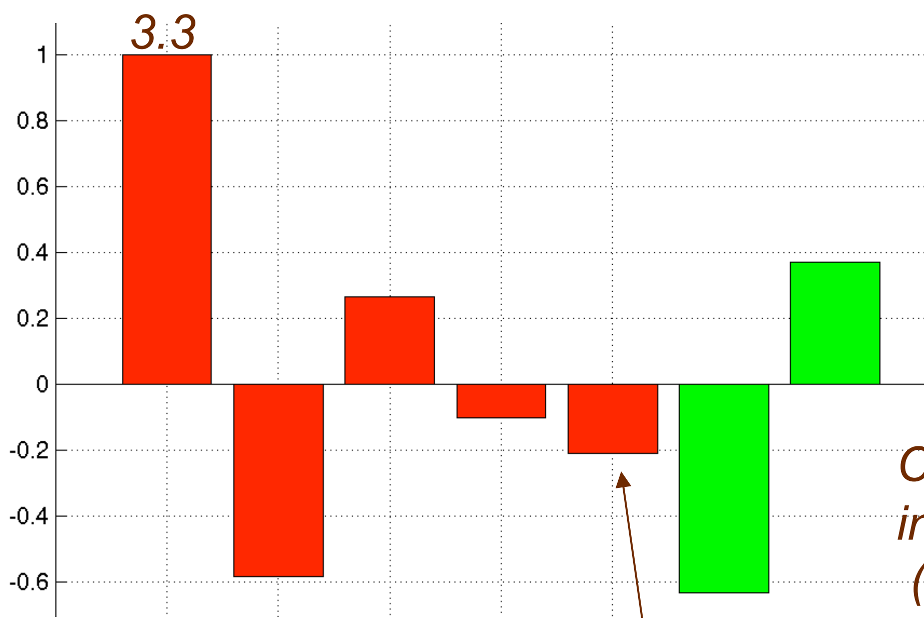
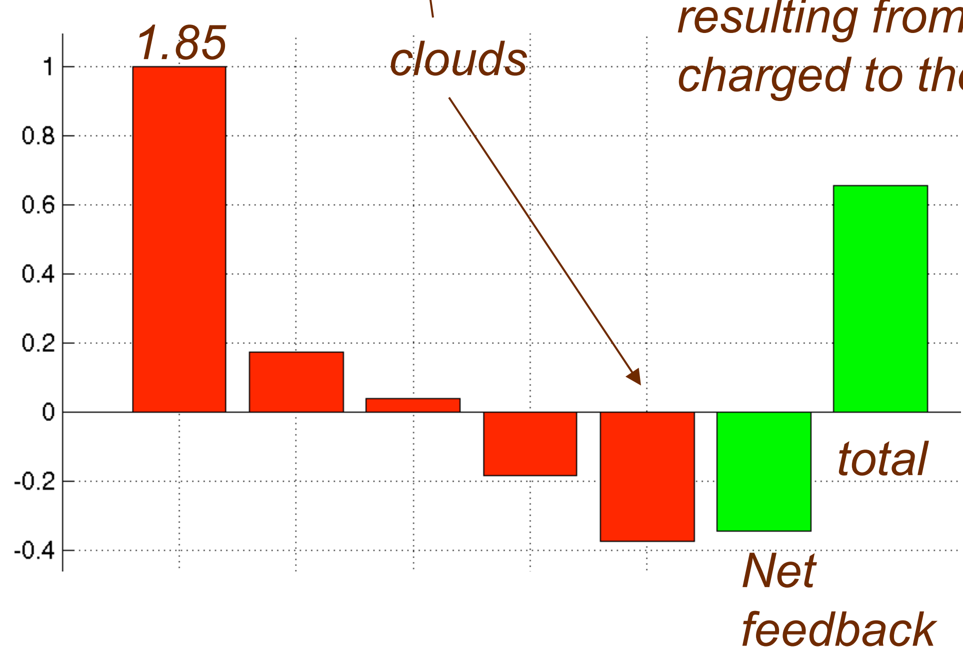
What if we choose
constant relative humidity
rather than constant specific humidity
as the base


Fixed rh
uniform T
base
fixed rh
lapse
rate
rh
Snow/
ice
clouds
Net
“feedback”
total
Wm-2K-1
2
1
0
-1
-2



Non-dimensional version



Clouds look like they have increased in importance (since water vapor change due to temperature change resulting from cloud change is now charged to the " cloud" account}

Observational constraints

- *20th century warming*
- *1000yr record*
- *Ice ages – LGM*
- *Deep time*

- *Volcanoes*
- *Solar cycle*
- *Internal Fluctuations*

- *Seasonal cycle etc*

Pliocene – could our models be this wrong on the latitudinal structure ?

Eos, Vol. 89, No. 49, 2 December 2008

21st century Warming IPCC

Pliocene reconstruction

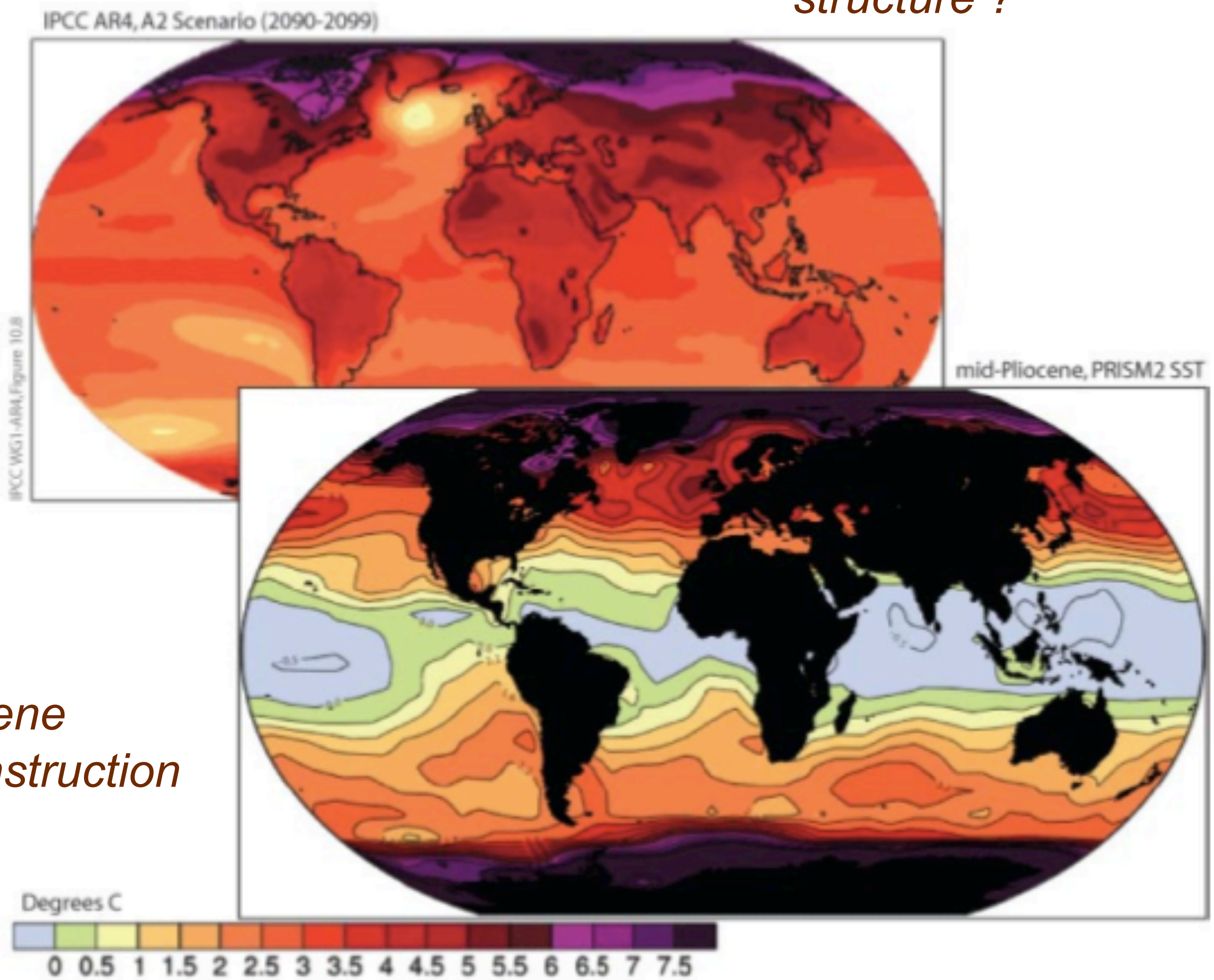
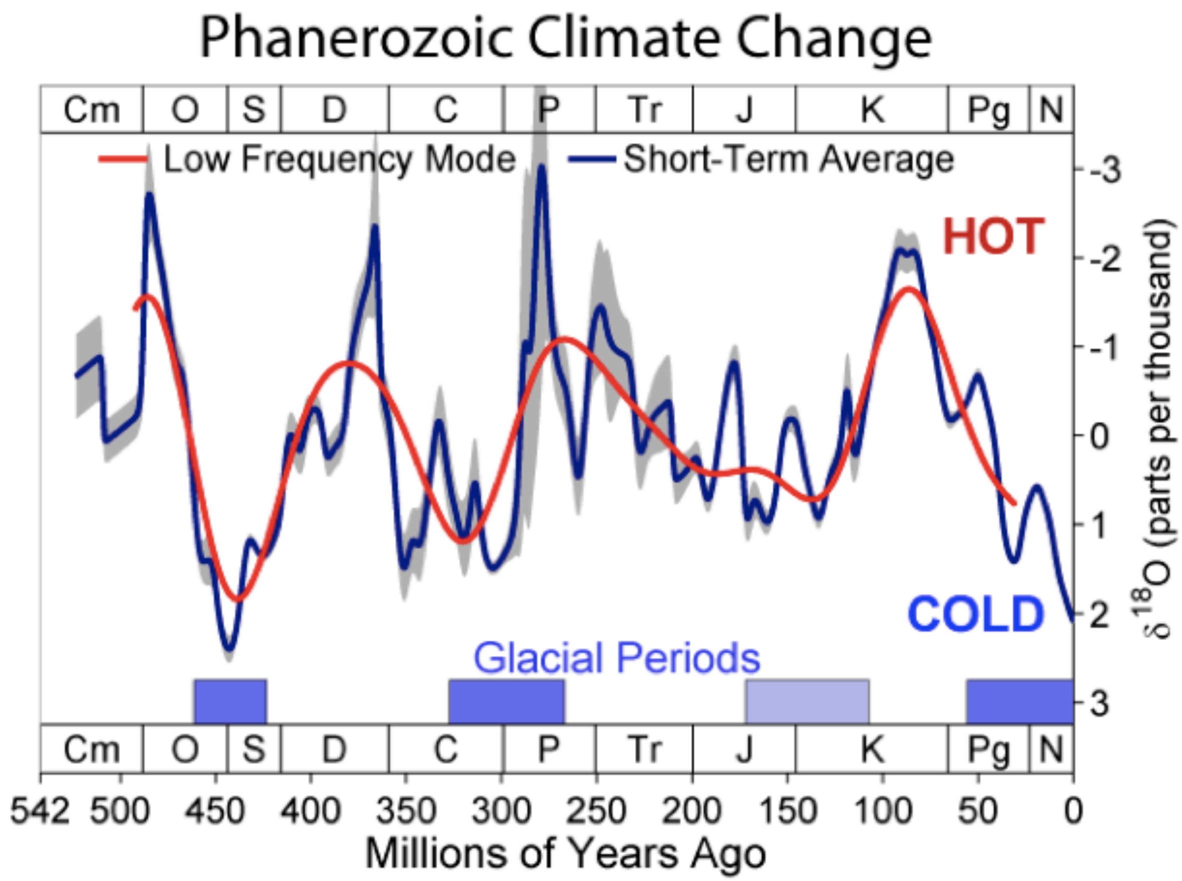


Fig. 2. Surface air temperature anomalies of (top) the late 21st century and (bottom) the mid-Pliocene.

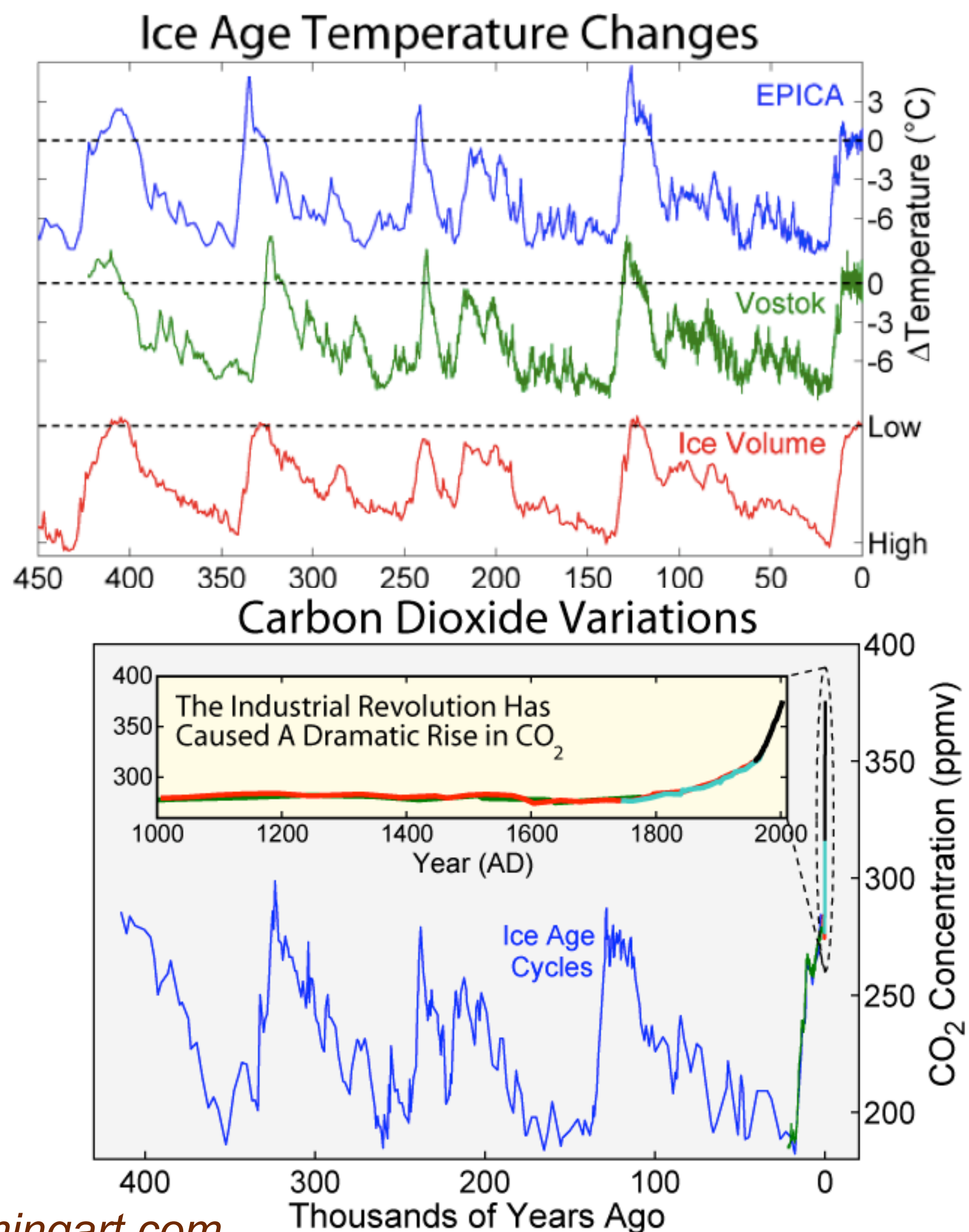
"We conclude that a climate sensitivity greater than 1.5 6C has probably been a robust feature of the Earth's climate system over the past 420 million years …"

Royer, Berner, Park; Nature 2007

CO_2 thought to be major driver of deep-time temperature variations



www.globalwarmingart.com



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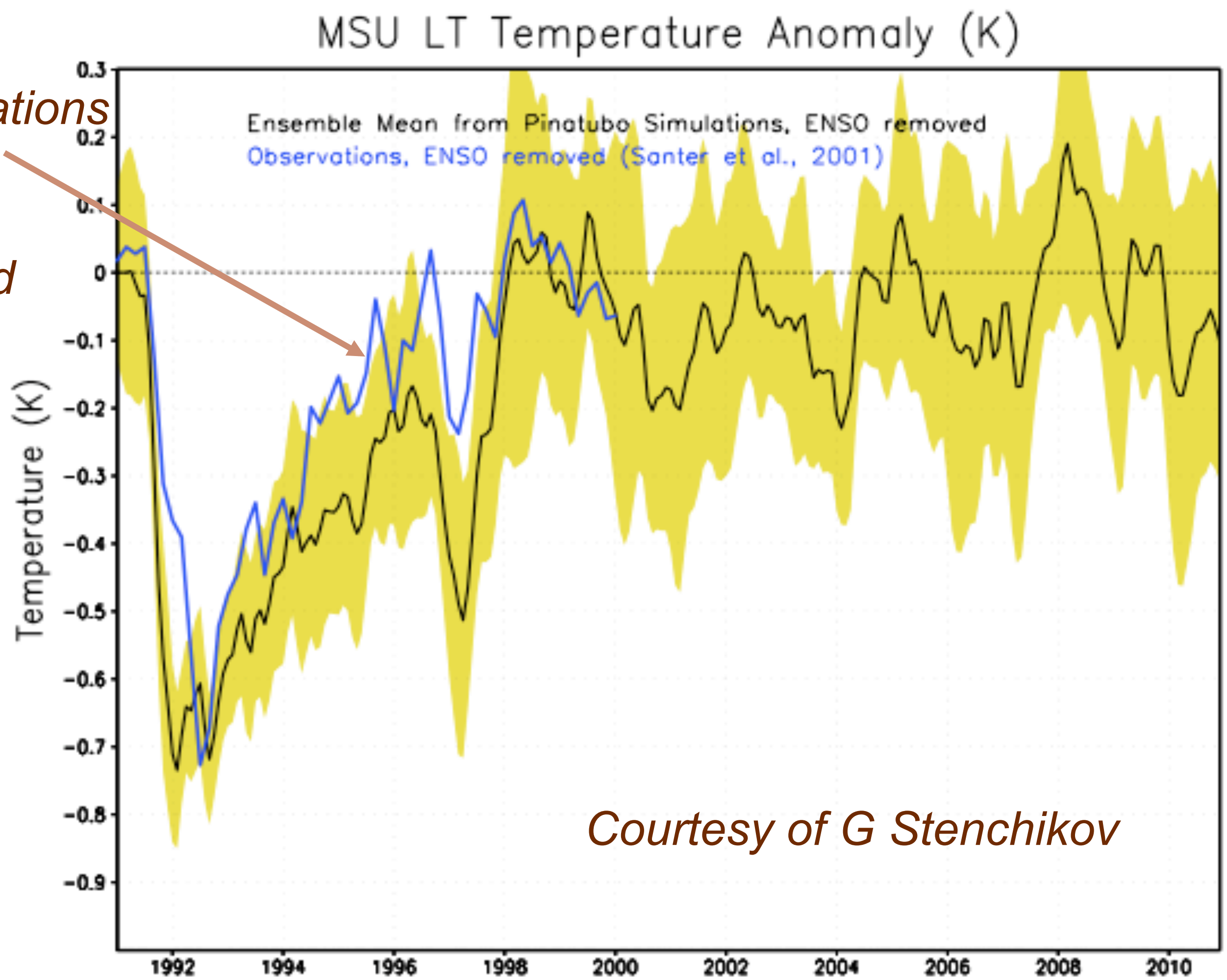
Global mean cooling due to Pinatubo volcanic eruption

Observations with El Nino removed



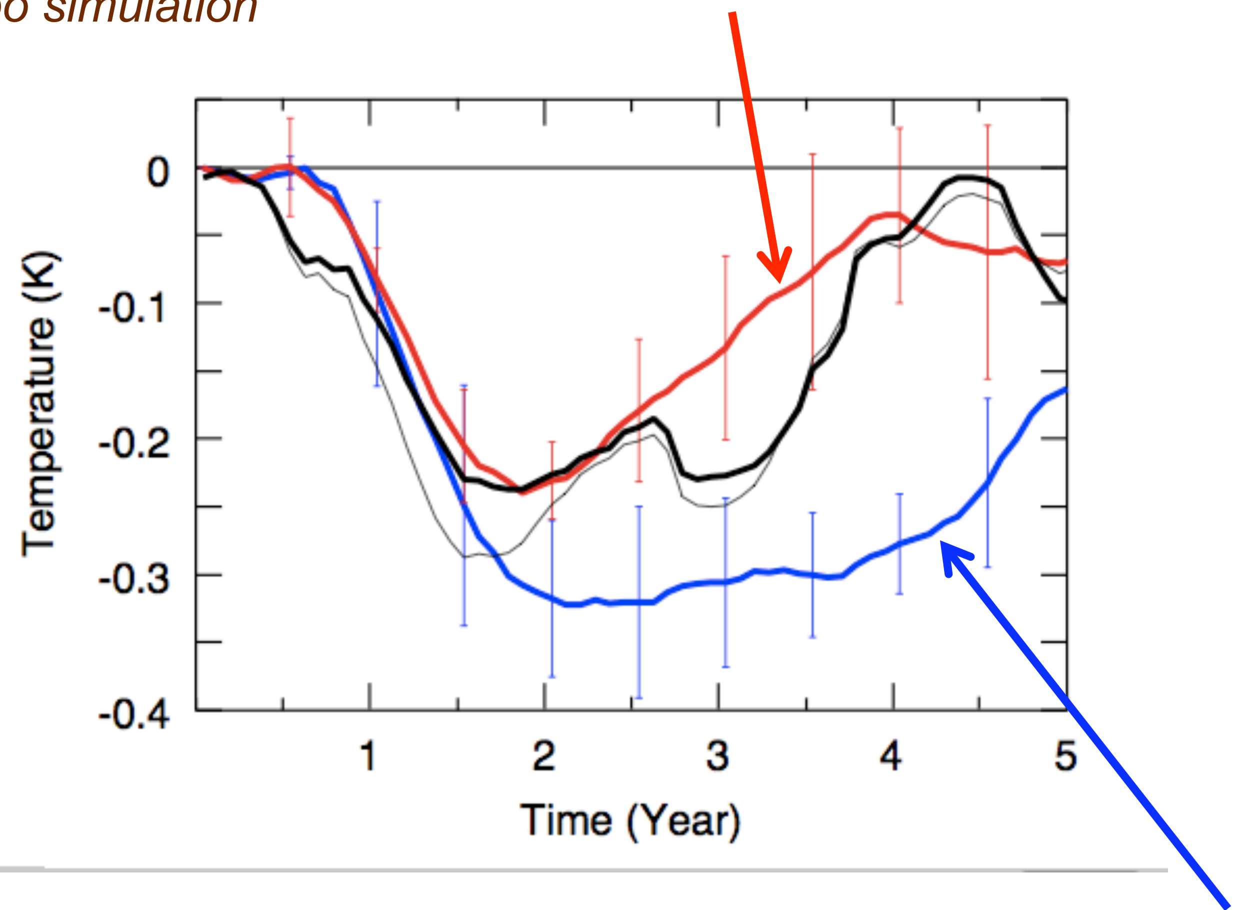
Courtesy of G Stenchikov

Range of ~10 Model Simulations GFDL CM2.1

Relaxation time after abrupt cooling contains information on climate sensitivity

Pinatubo simulation

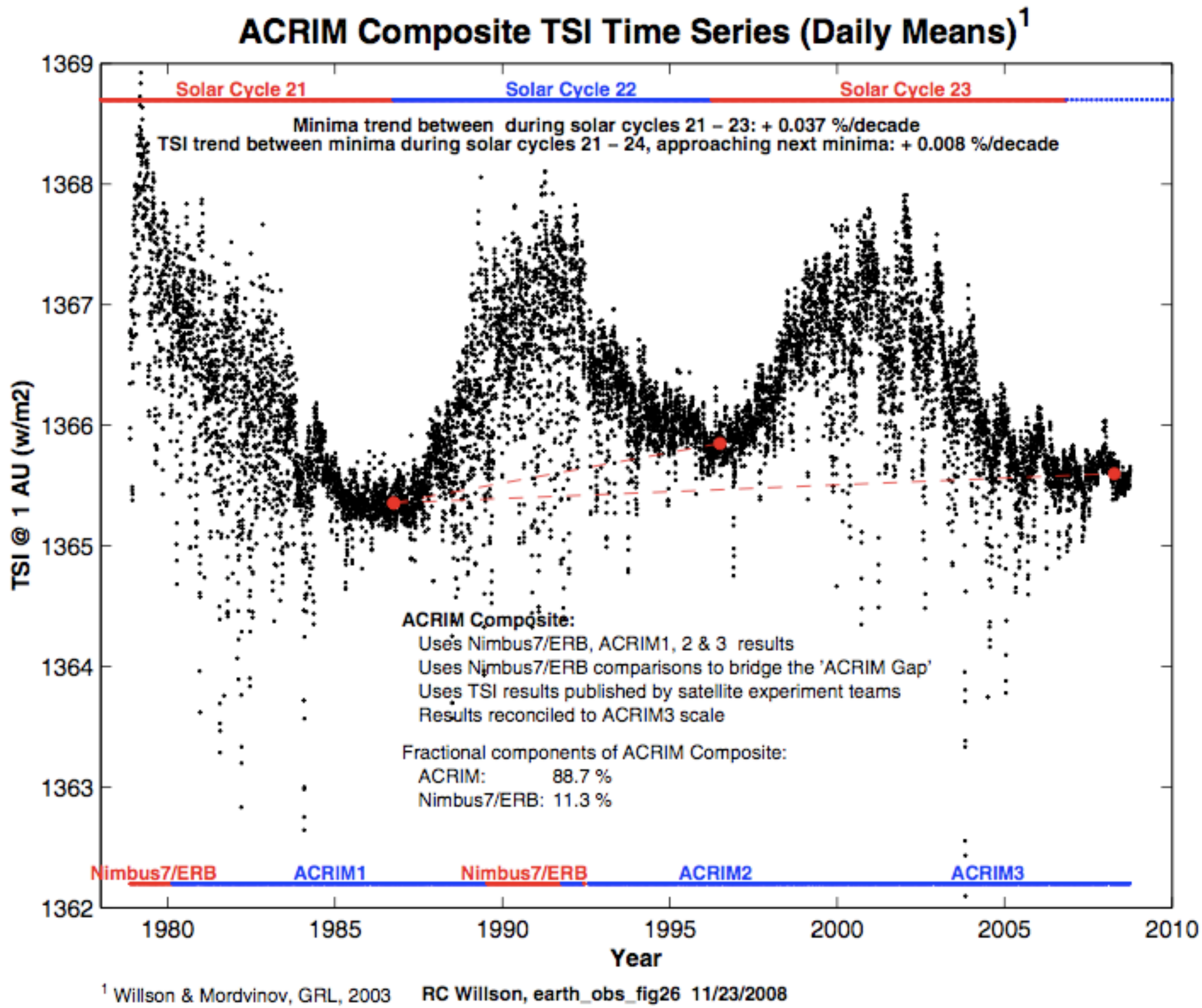
Low sensitivity model

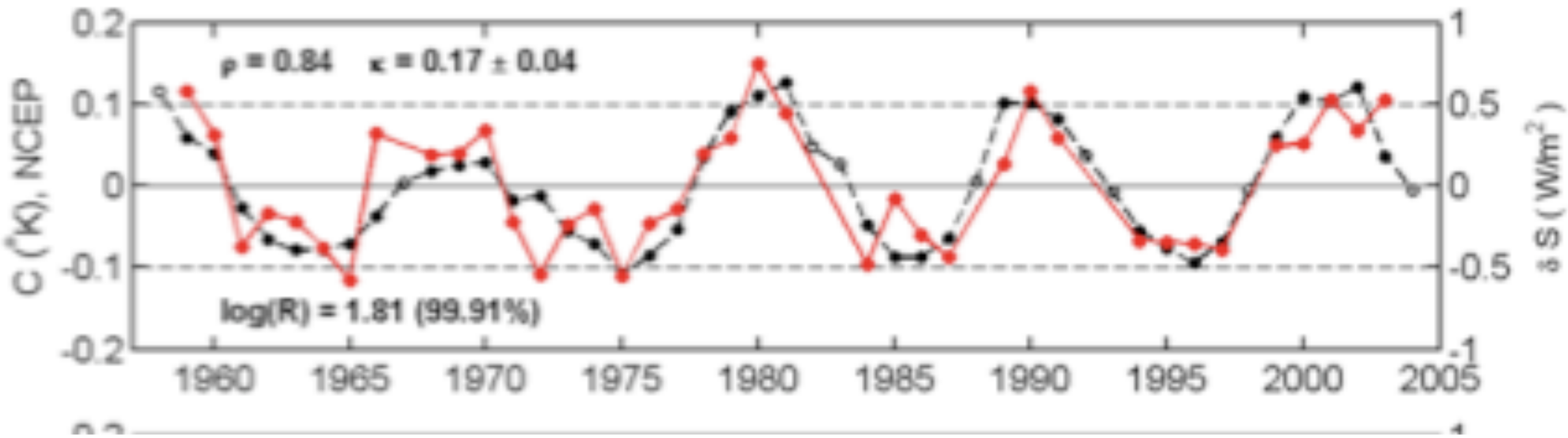


High sensitivity model

Yokohata, et al, 2005

Observed total solar irradiance variations in 11yr solar cycle (~ 0.2% peak-to-peak)

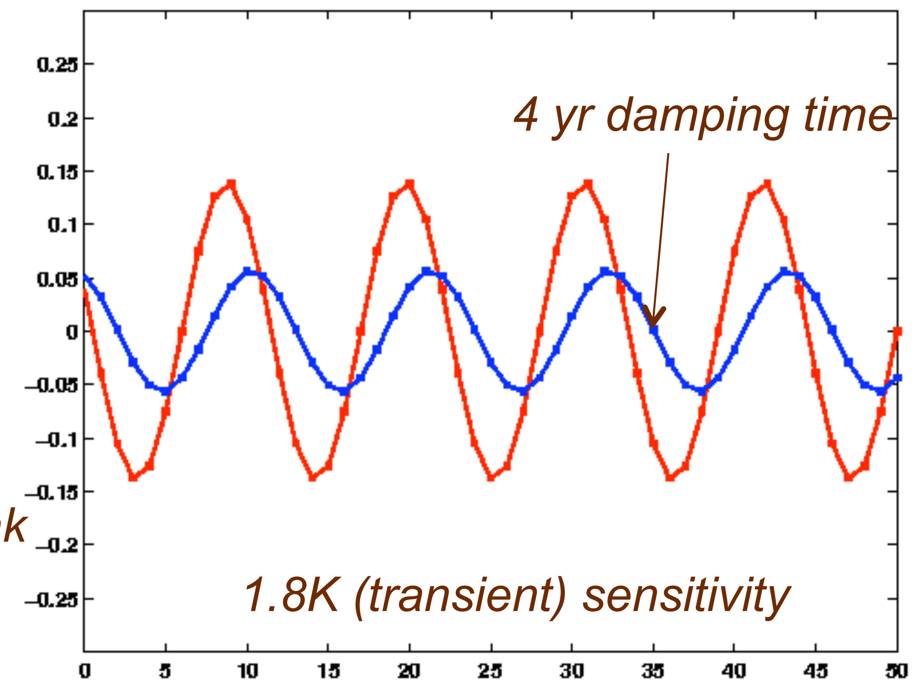


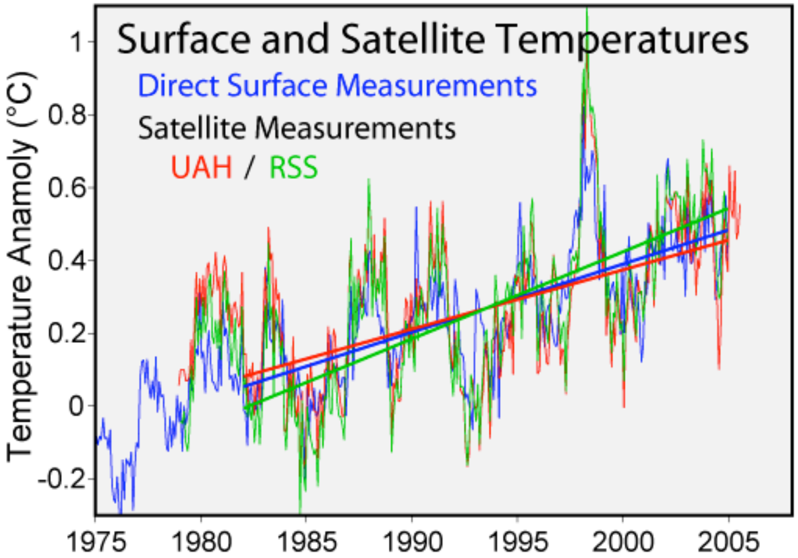


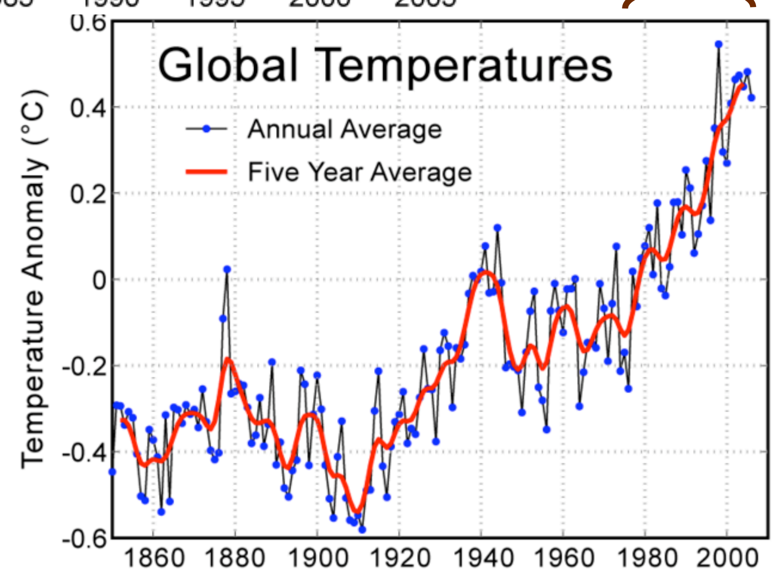
Tung et al =>
0.2K peak to peak
(other studies yield only 0.1K)

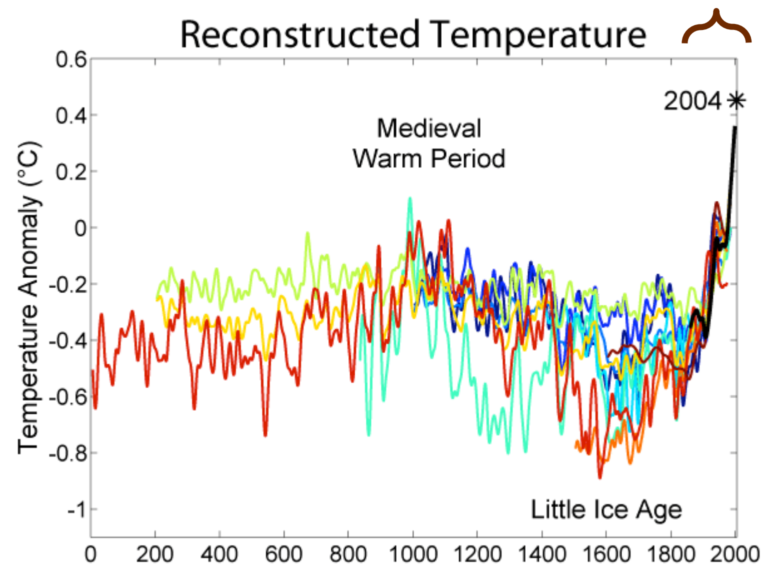
Seems to imply large transient sensitivity

Only gives
0.05 peak to peak





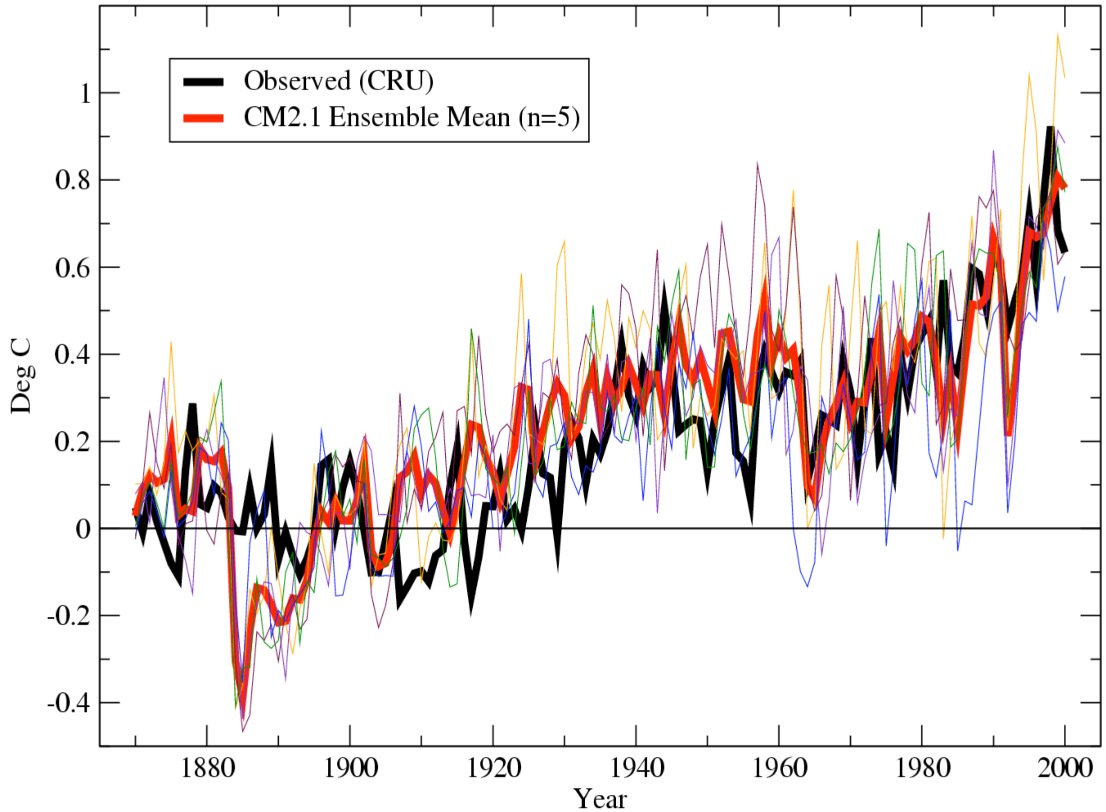




www.globalwarmingart.com

Global Mean Surface Temperature: CM2.1 vs. Observed

version: scenarios minus long-term trends; combined sst/t_ref; masked; 1881-1920 ref

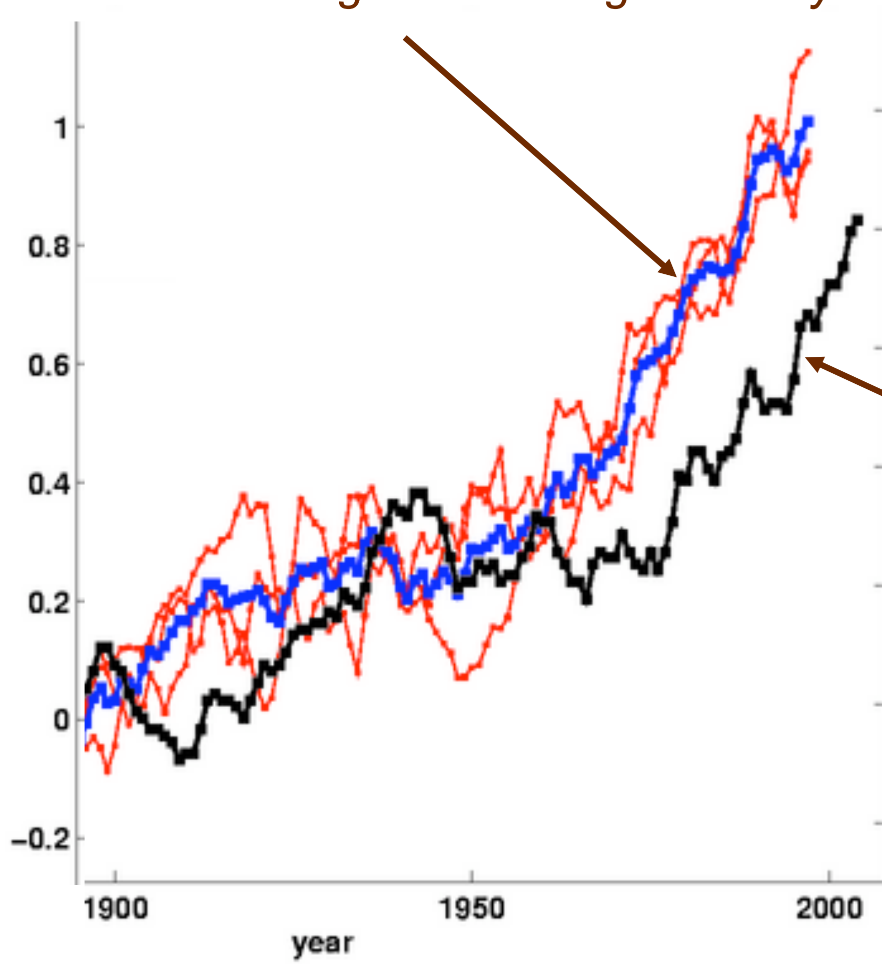


(GFDL CM2.1 -- Includes estimates of volcanic and anthropogenic aerosols, as well as estimates of variations in solar irradiance)

Models can produce very good fits by including aerosol effects, but models with stronger aerosol forcing and higher climate sensitivity are also viable (and vice-versa)

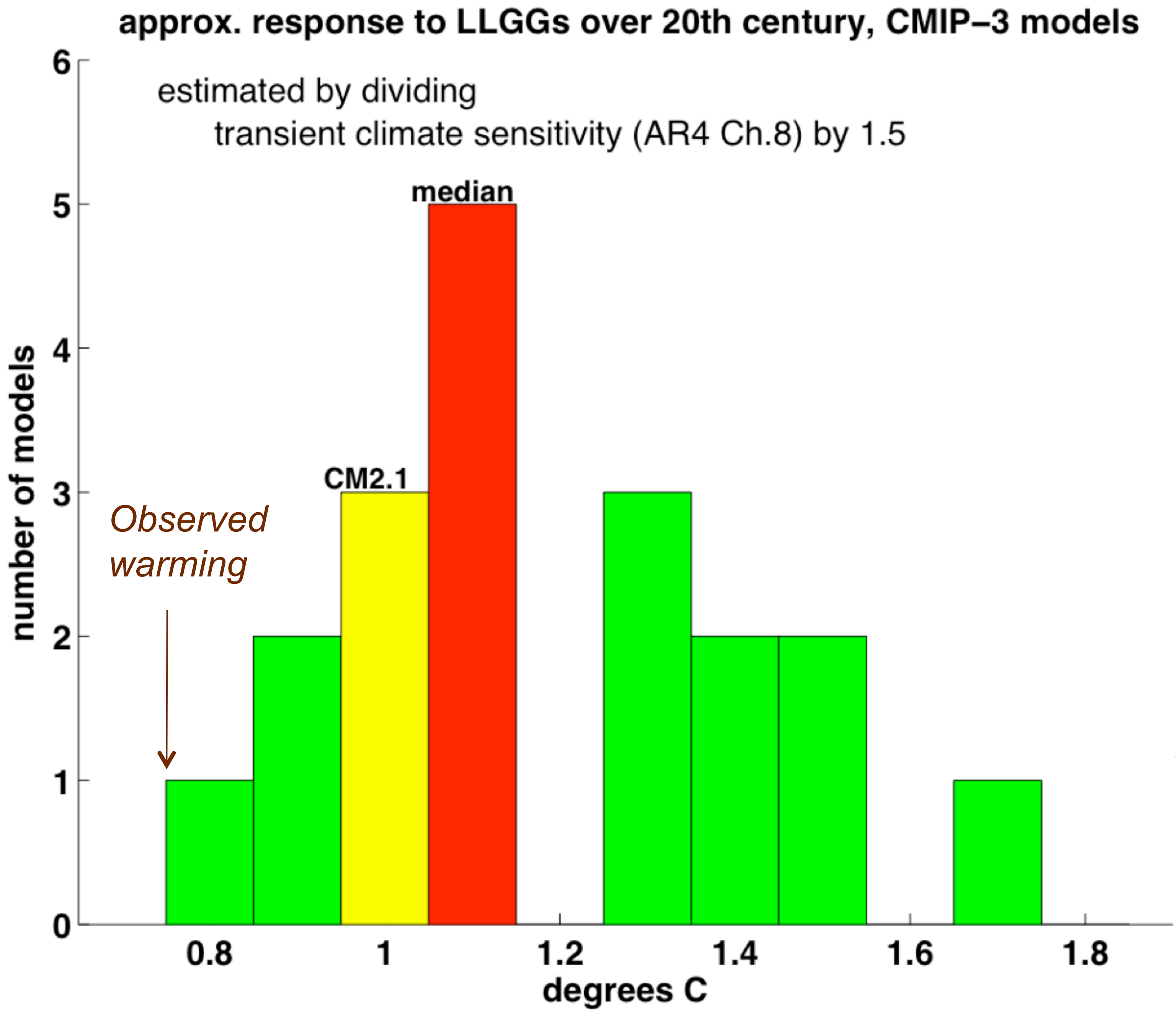
GFDL's CM2.1 with well-mixed greenhouse gases only

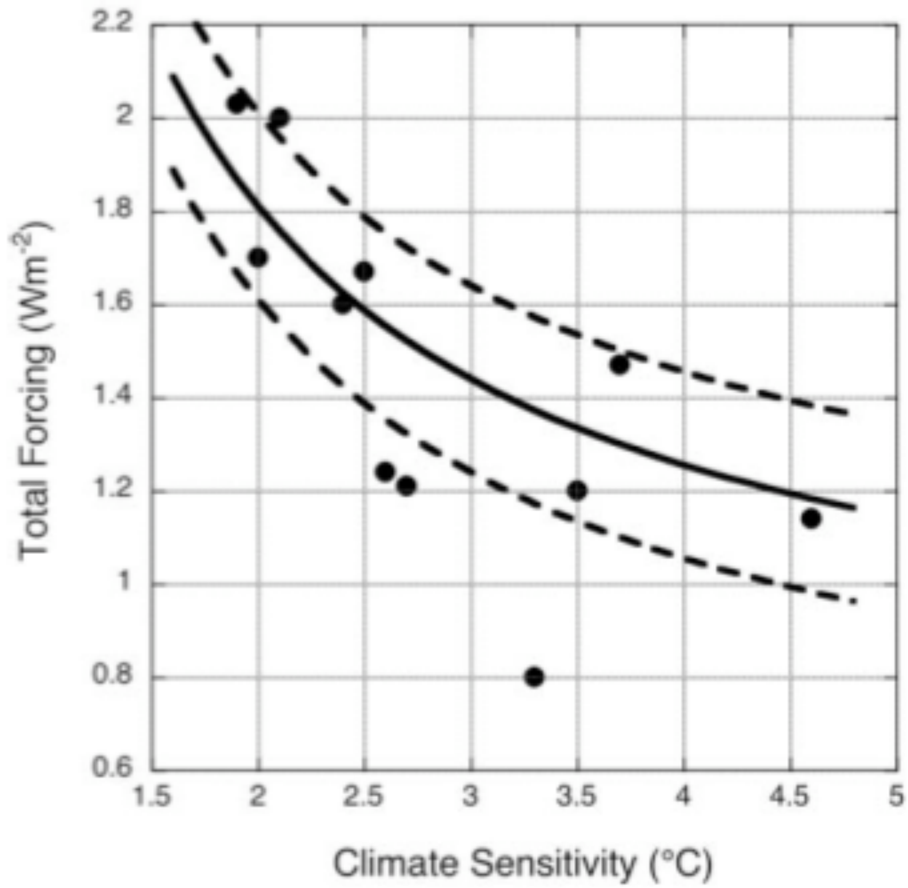
Global mean temperature change



Observations (GISS)

"It is likely that increases in greenhouse gas concentrations alone would have caused more warming than observed because volcanic and anthropogenic aerosols have offset some warming that would otherwise have taken place." (AR4 WG1 SPM).

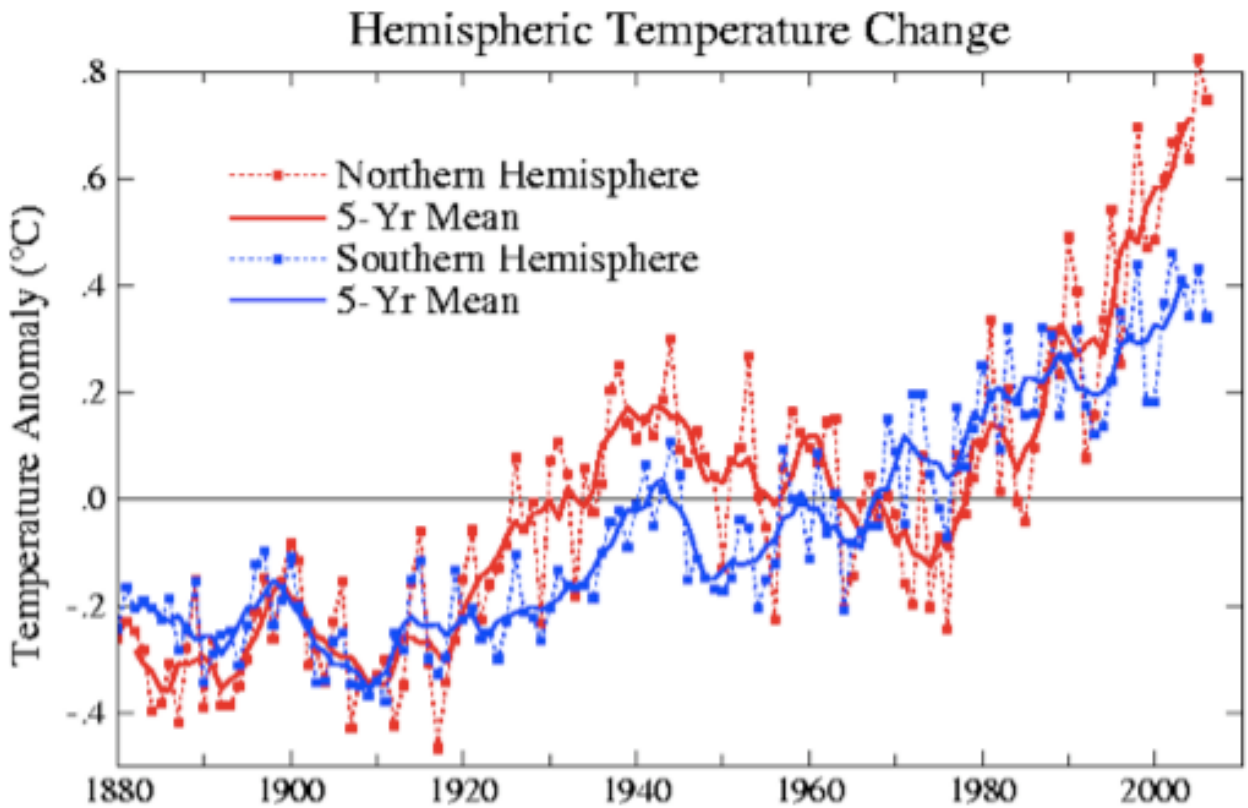

approx. response to LLGGs over 20th century, CMIP–3 models
estimated by dividing
transient climate sensitivity (AR4 Ch.8) by 1.5
median
CM2.1
Observed
warming
number of models
degrees C
0
1
2
3
4
5
6
0.8
1
1.2
1.4
1.6
1.8



Kiehl, 2008: In AR4, forcing over 20th century and equilibrium climate sensitivity negatively correlated

How would this look for transient climate sensitivity?

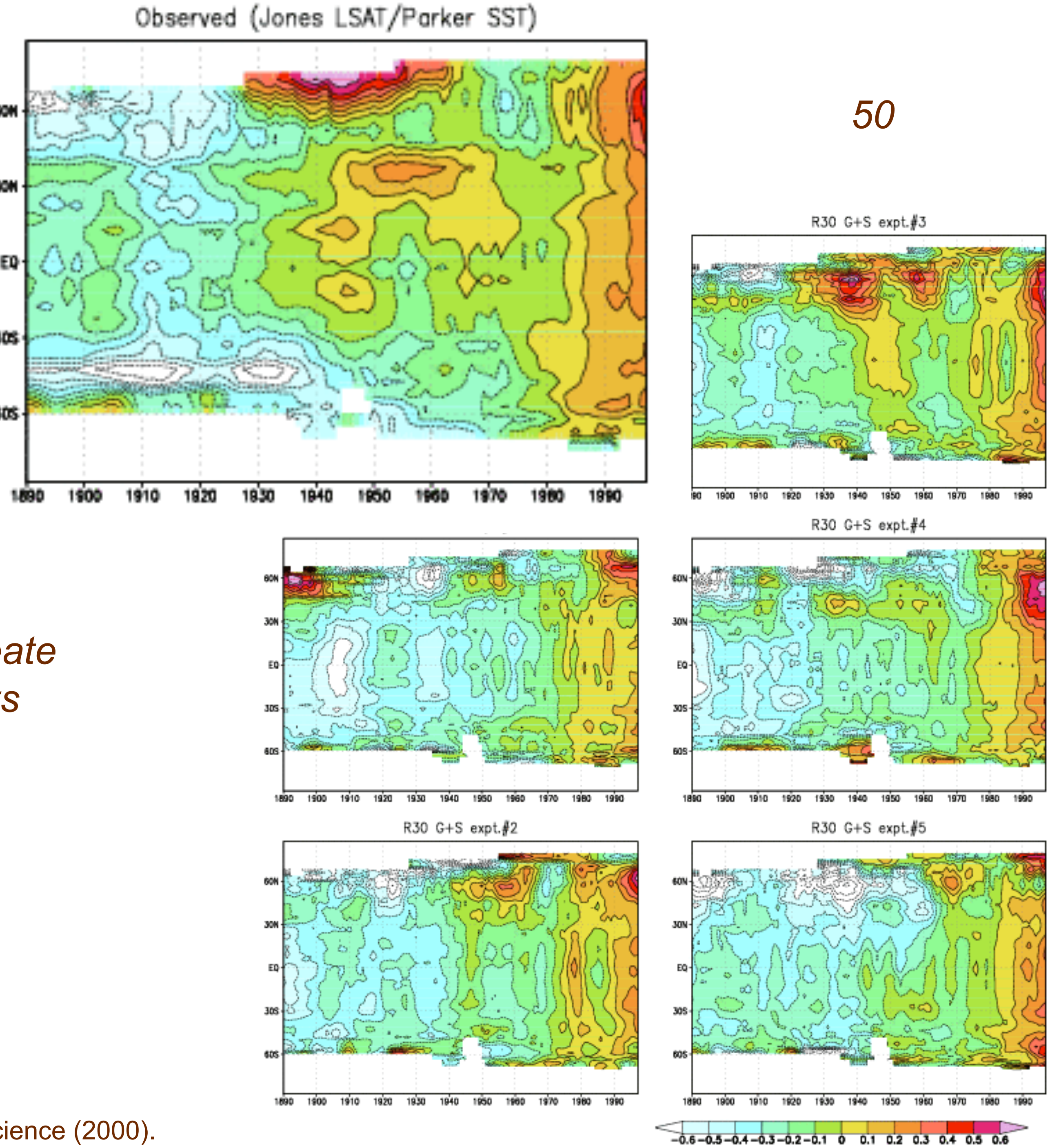
Do interhemispheric differences in warming provide a simple test of aerosol forcing changes over time?



http://data.giss.nasa.gov/gistemp/

temperature anomalies (10yr running means) averaged around latitude circles over 20th century:

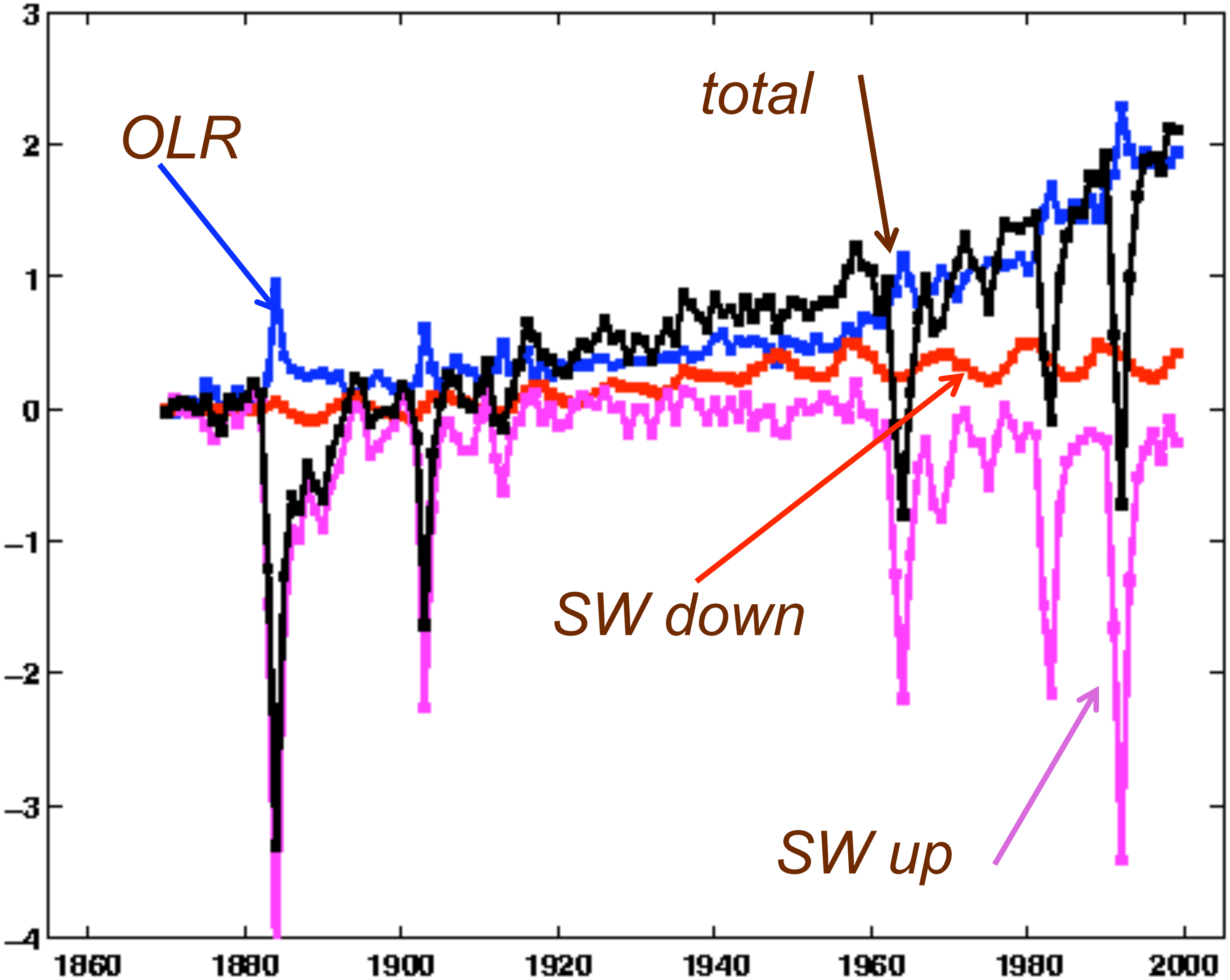
-- Observations (big)
-- 5 realizations of a model simulation (small)



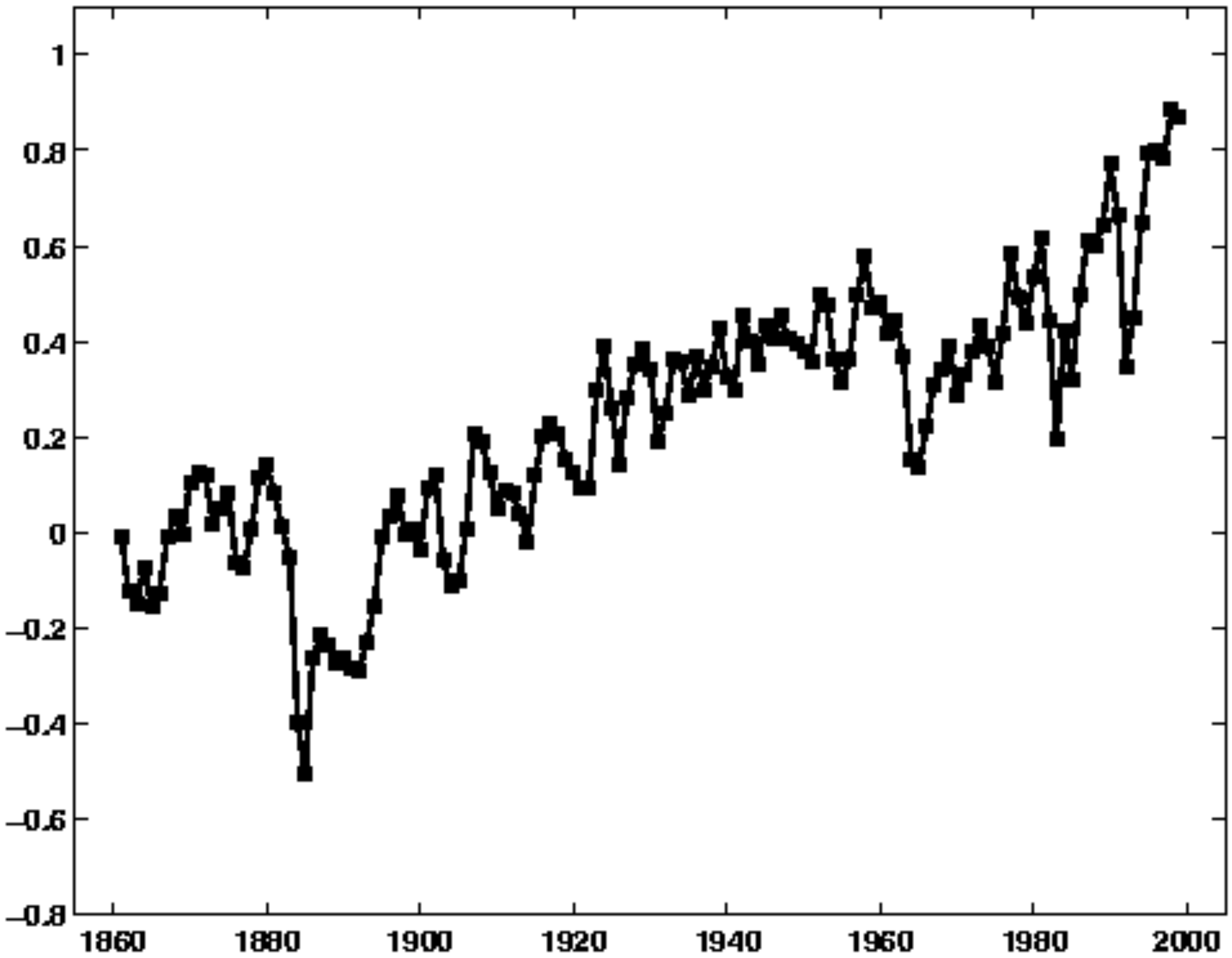
Internal variability can create Interhemispheric gradients

Source: Delworth and Knutson, Science (2000).

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

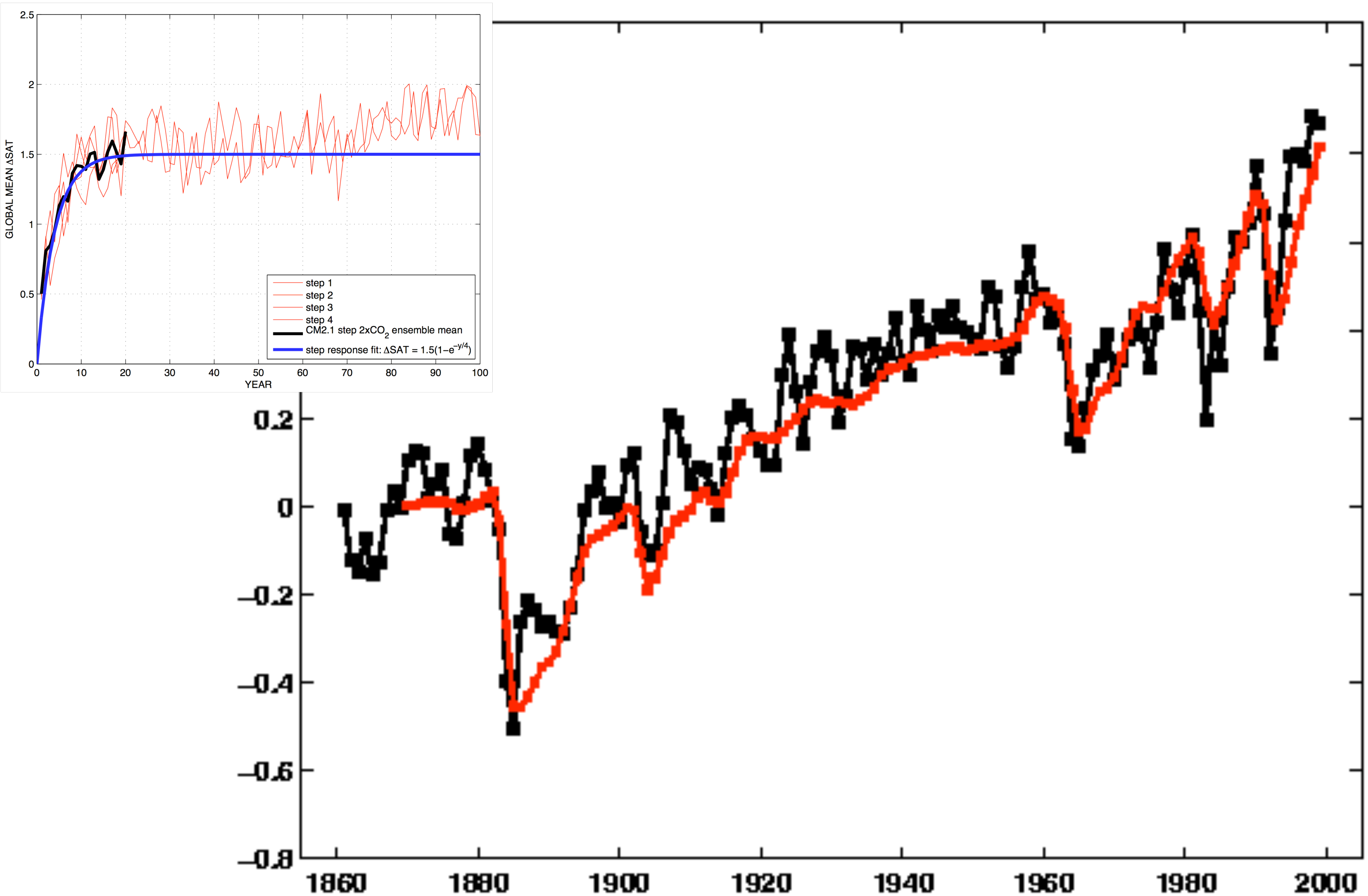


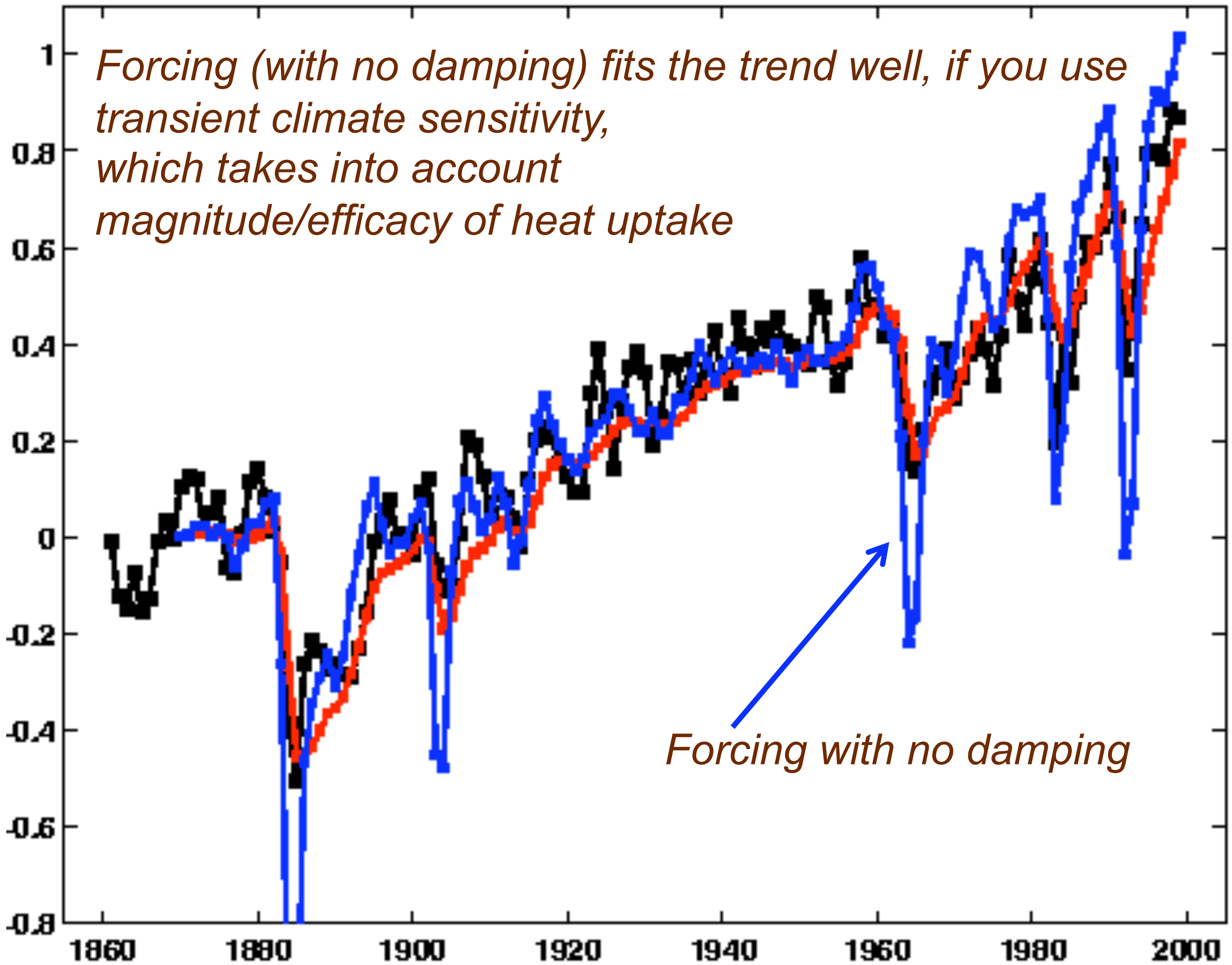
Temperature change averaged over 5 realizations of coupled model



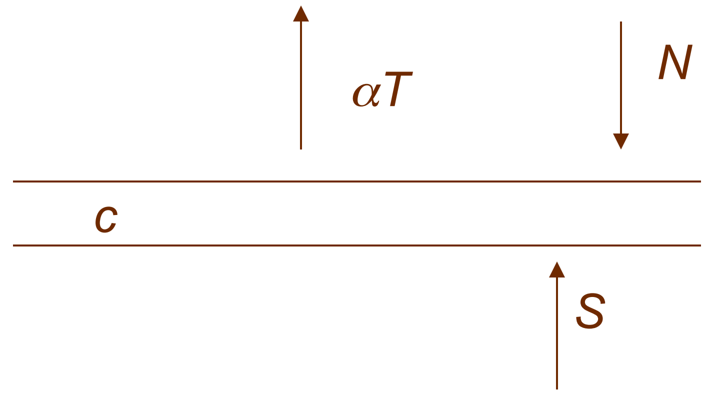
Fit with

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




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

Why can't we just look at
the TOA fluxes and
surface temperatures?
TOA record is short,
But there are other issues



Spenser-Braswell, 2008

$$c\frac{\partial T}{\partial t} = S + N - \alpha T$$

(Assuming no forcing)

Suppose N isTOA noise, but correlated with T because it forces T

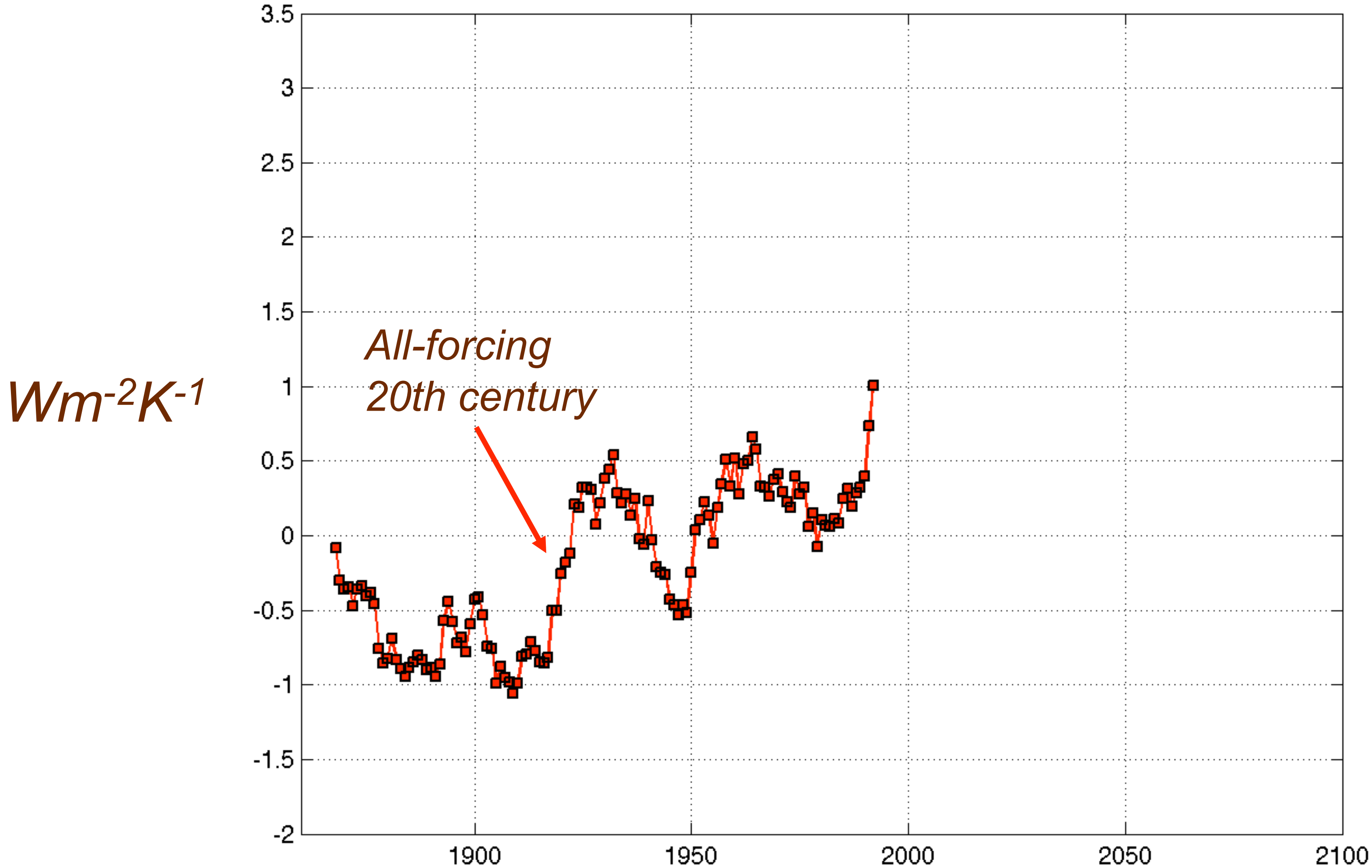
Regressing flux with T

$$-\frac{\langle (N-\alpha T)T \rangle}{\langle T^2 \rangle} = \alpha'$$

If S and N are uncorrelated
and have the same spectrum
one can show that

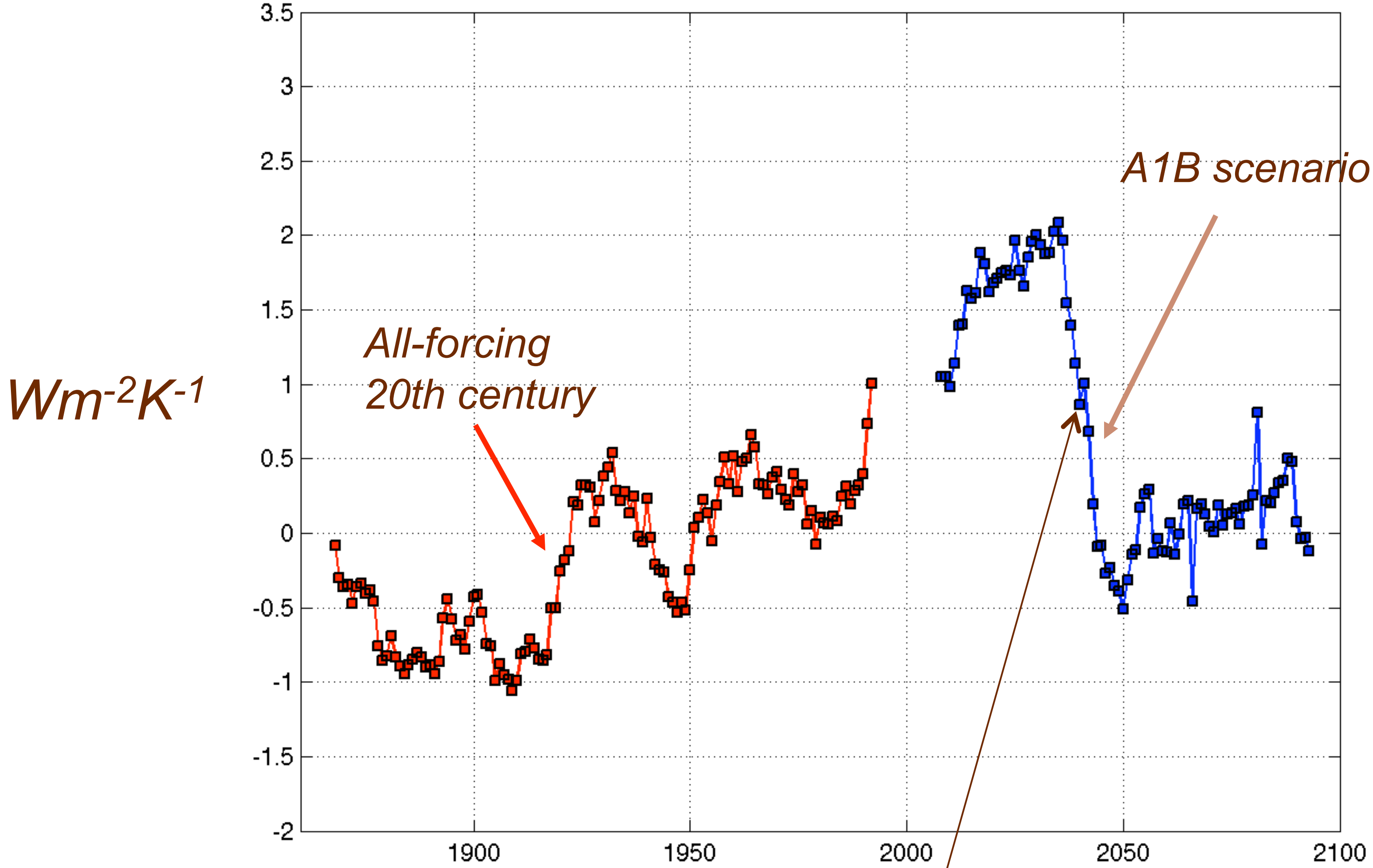
$$\alpha' = \alpha \frac{\langle N^2 \rangle}{\langle N^2 \rangle + \langle S^2 \rangle} < \alpha$$

Shortwave regression across ensemble,
following K. Swanson 2008



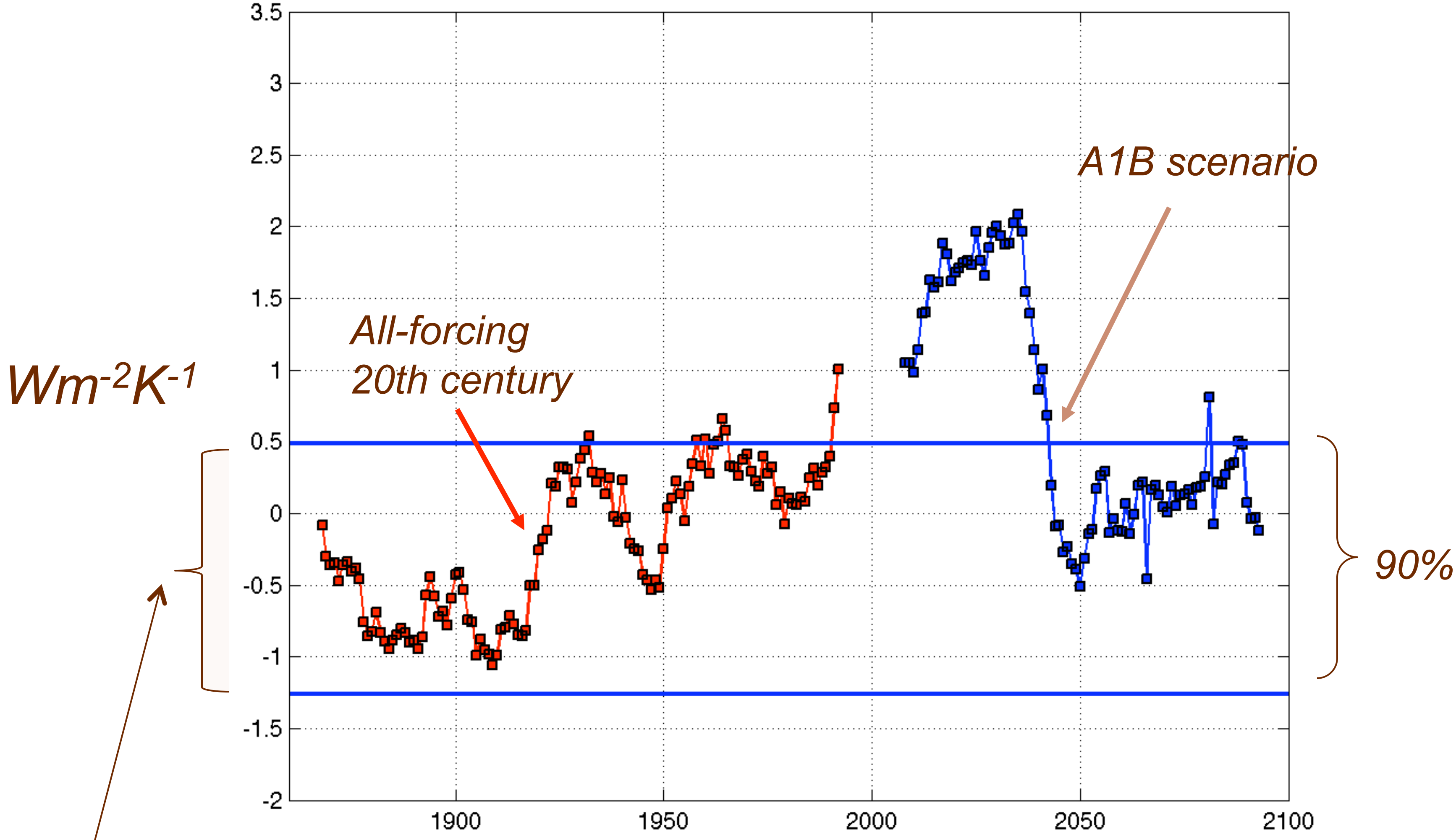
Following an idea of K. Swanson,
take a set of realizations of the 20th century from one model,
and correlate global mean TOA with surface temperature across the ensemble

Shortwave regression across ensemble,
following K. Swanson 2008



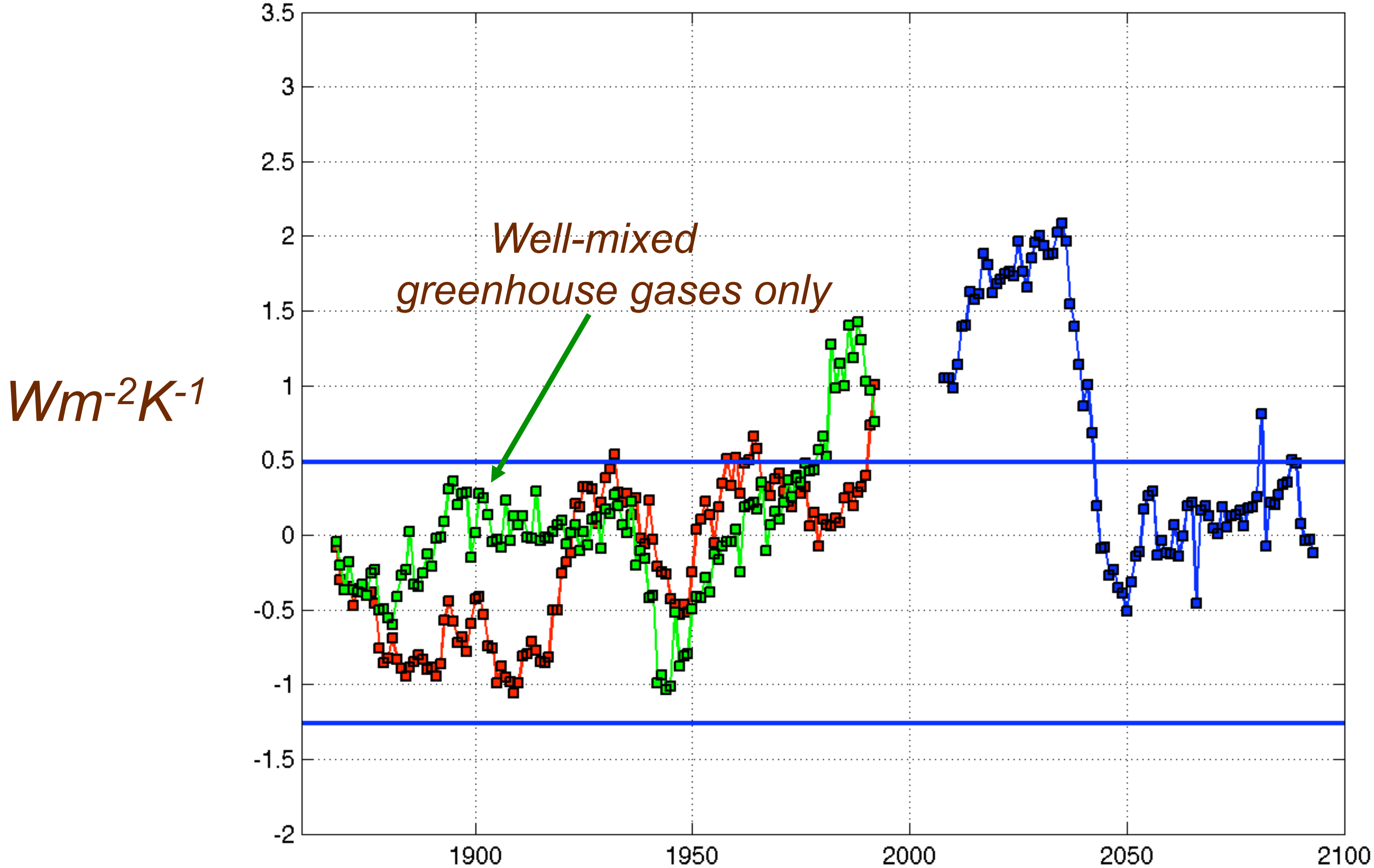
Is this a sign of non-linearity? What is this?

Shortwave regression across ensemble, following K. Swanson 2008

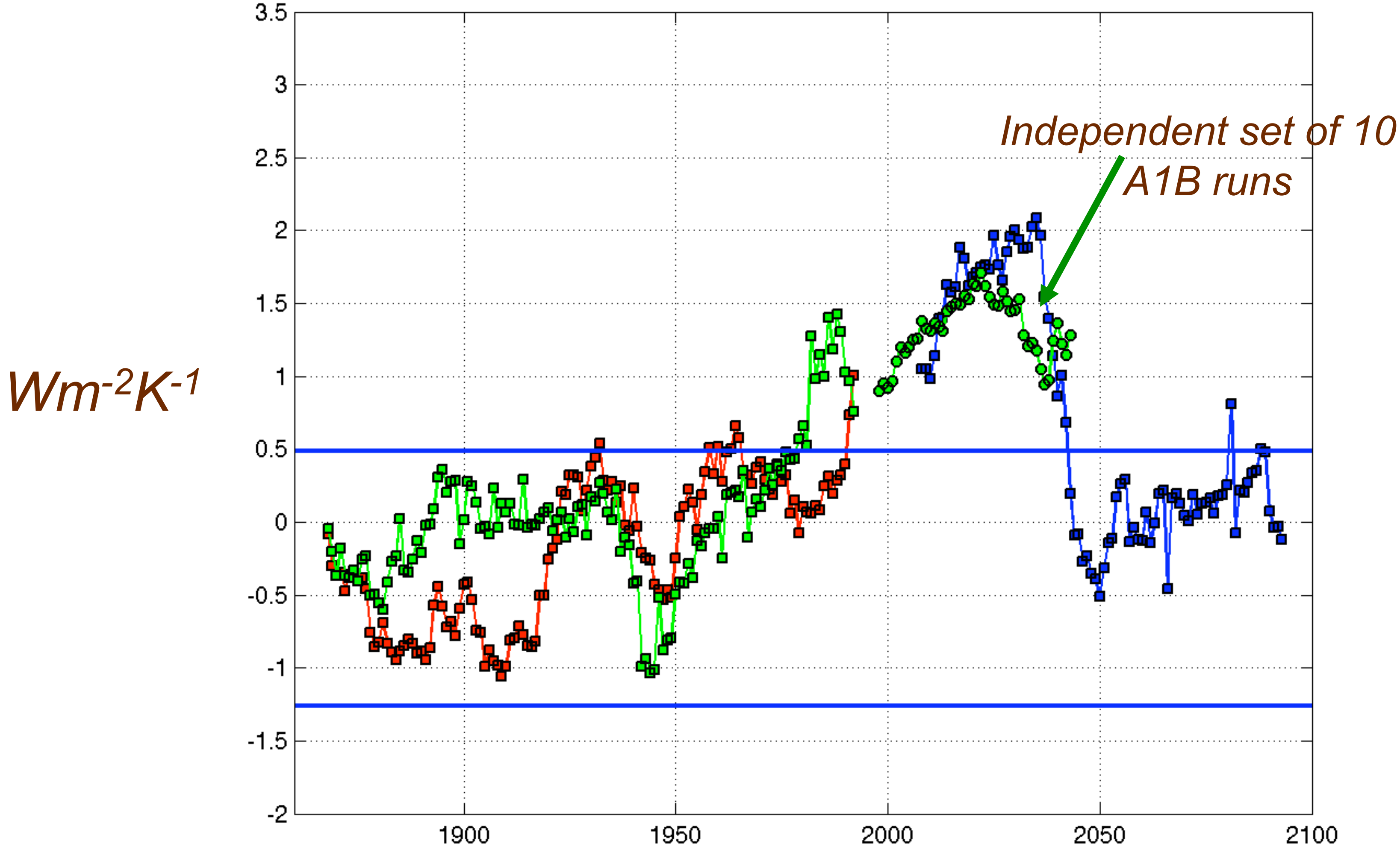


Estimate of noise in this statistic from 2000yr control run

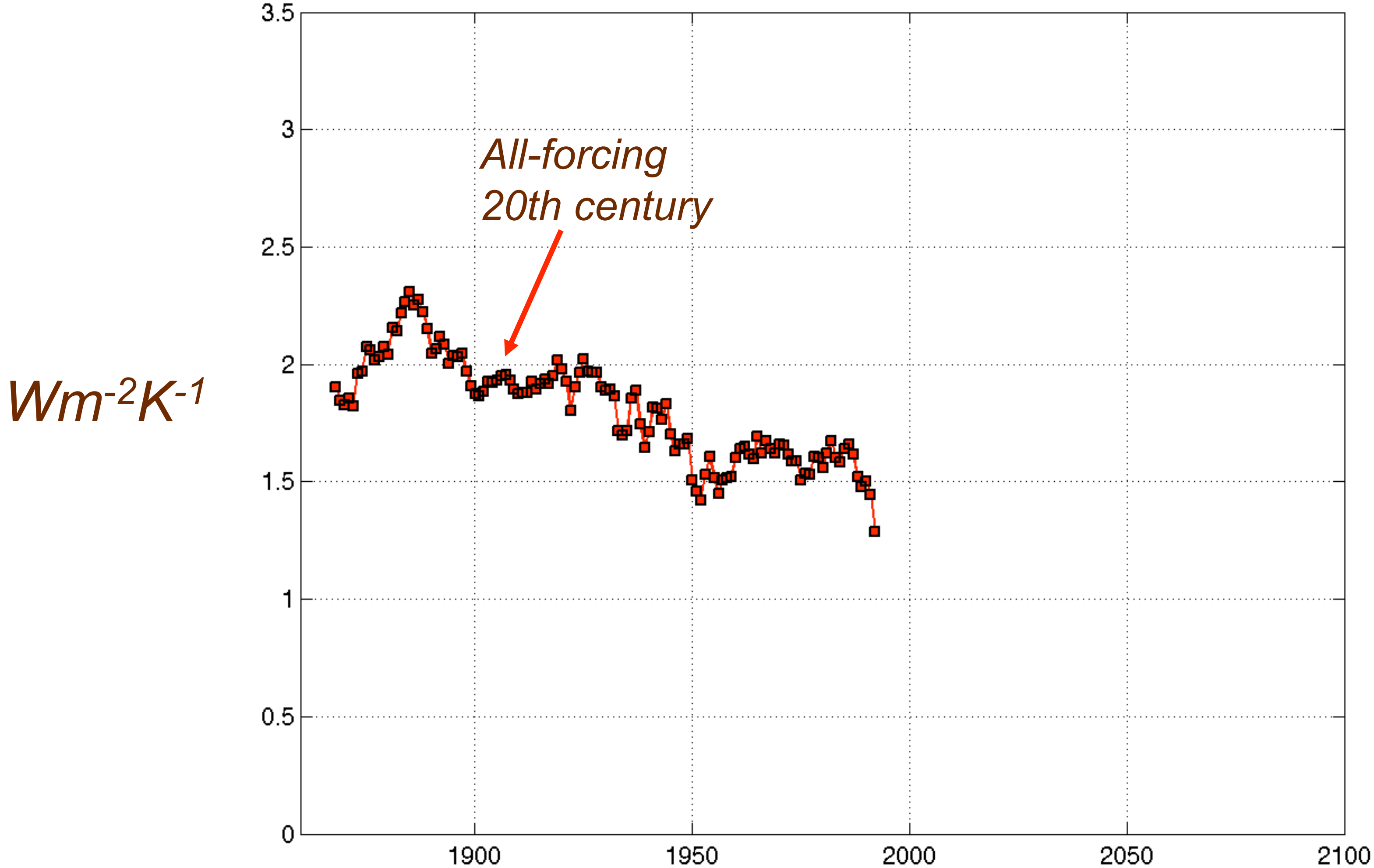
Shortwave regression across ensemble, following K. Swanson 2008



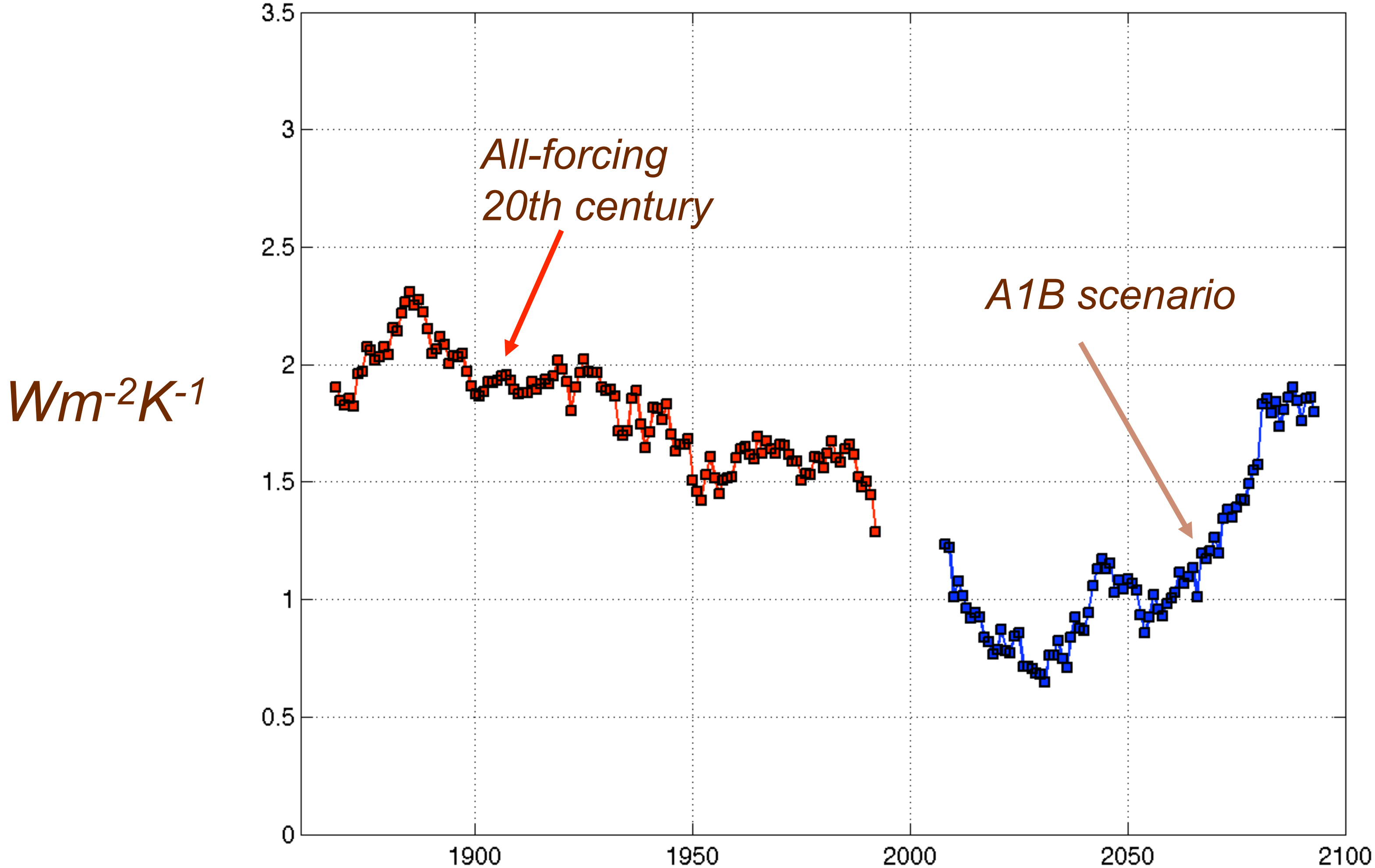
Shortwave regression across ensemble, following K. Swanson 2008



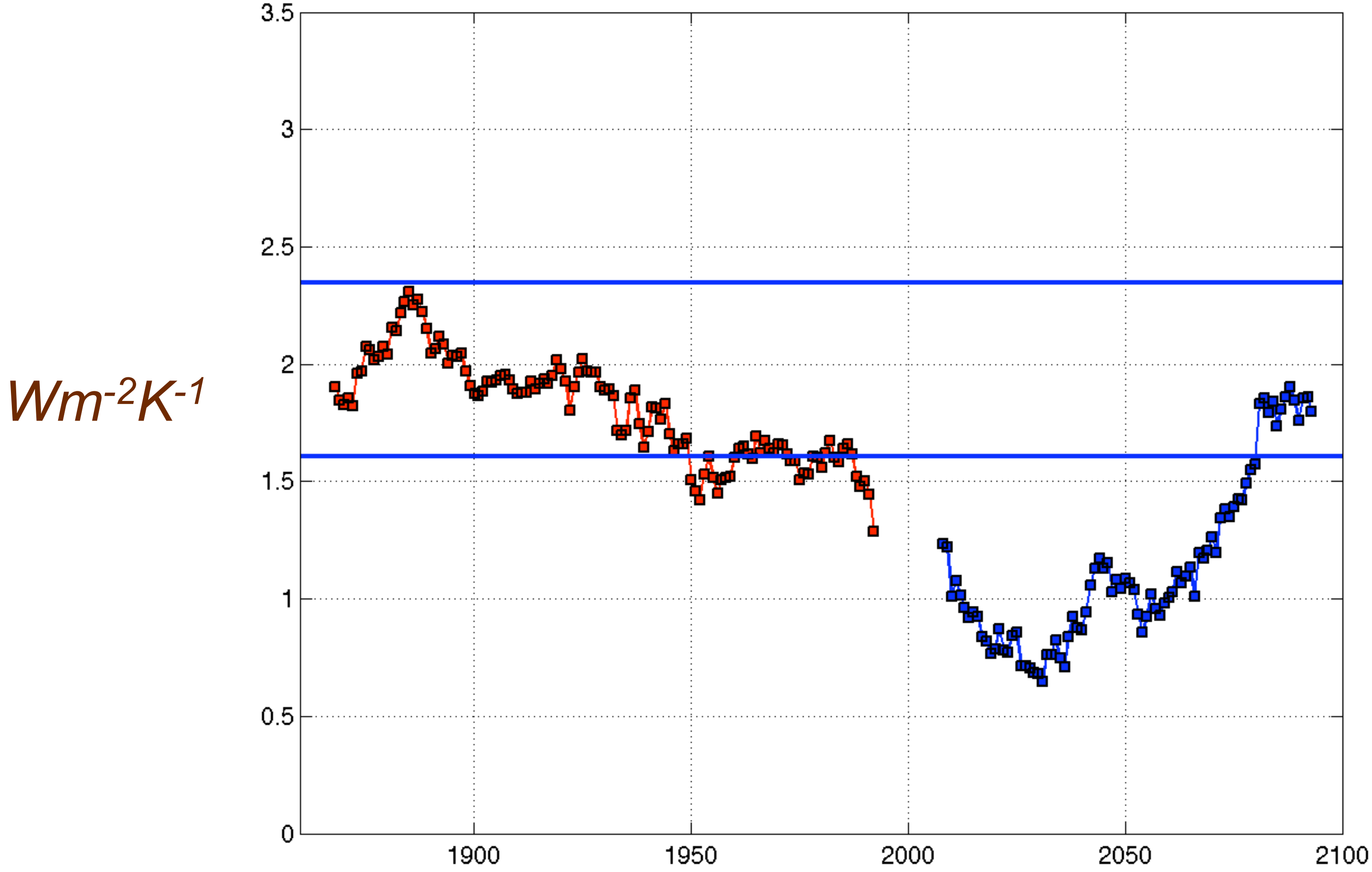
Longwave regression across ensemble,
following K. Swanson 2008

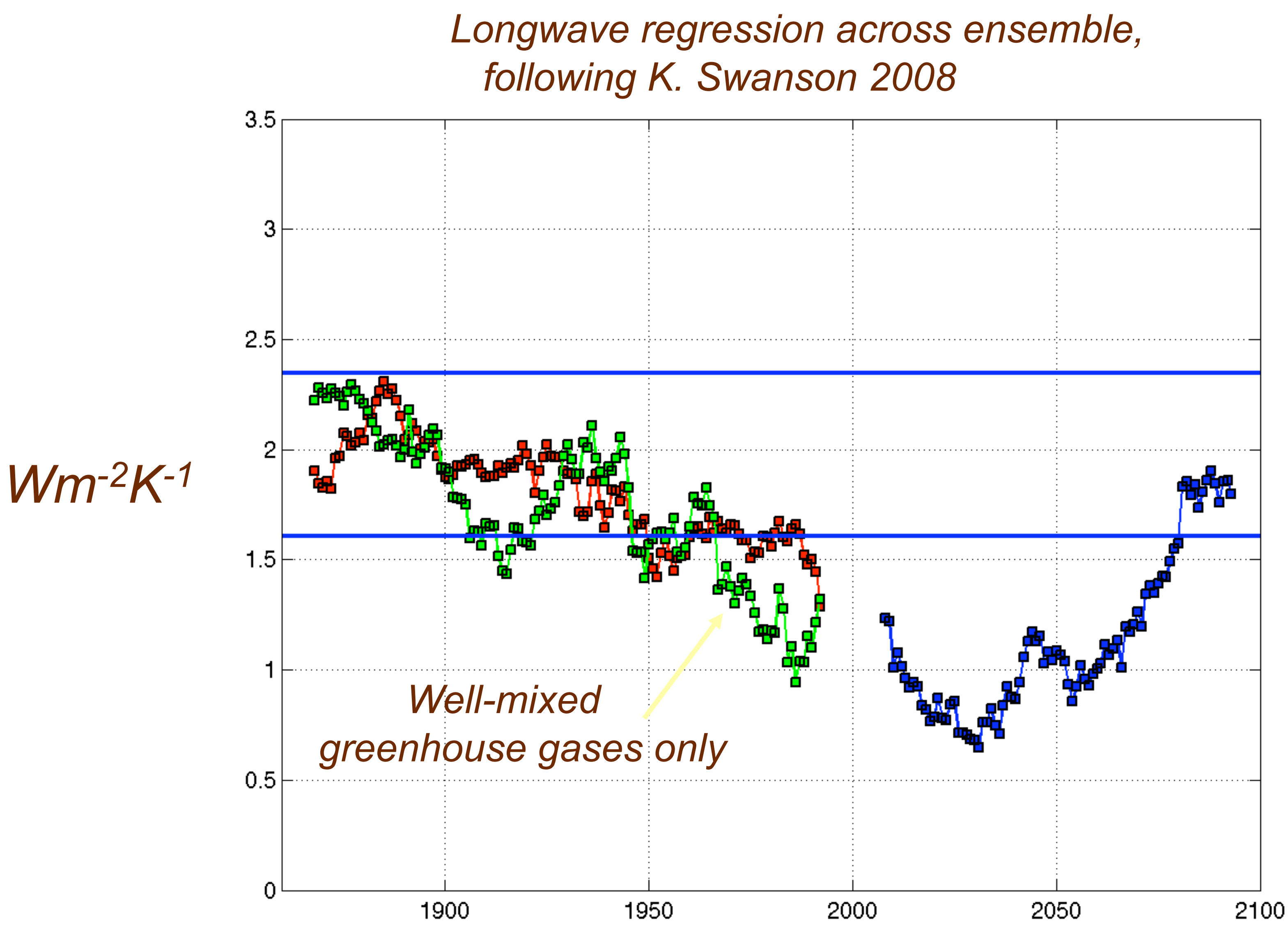


Longwave regression across ensemble, following K. Swanson 2008



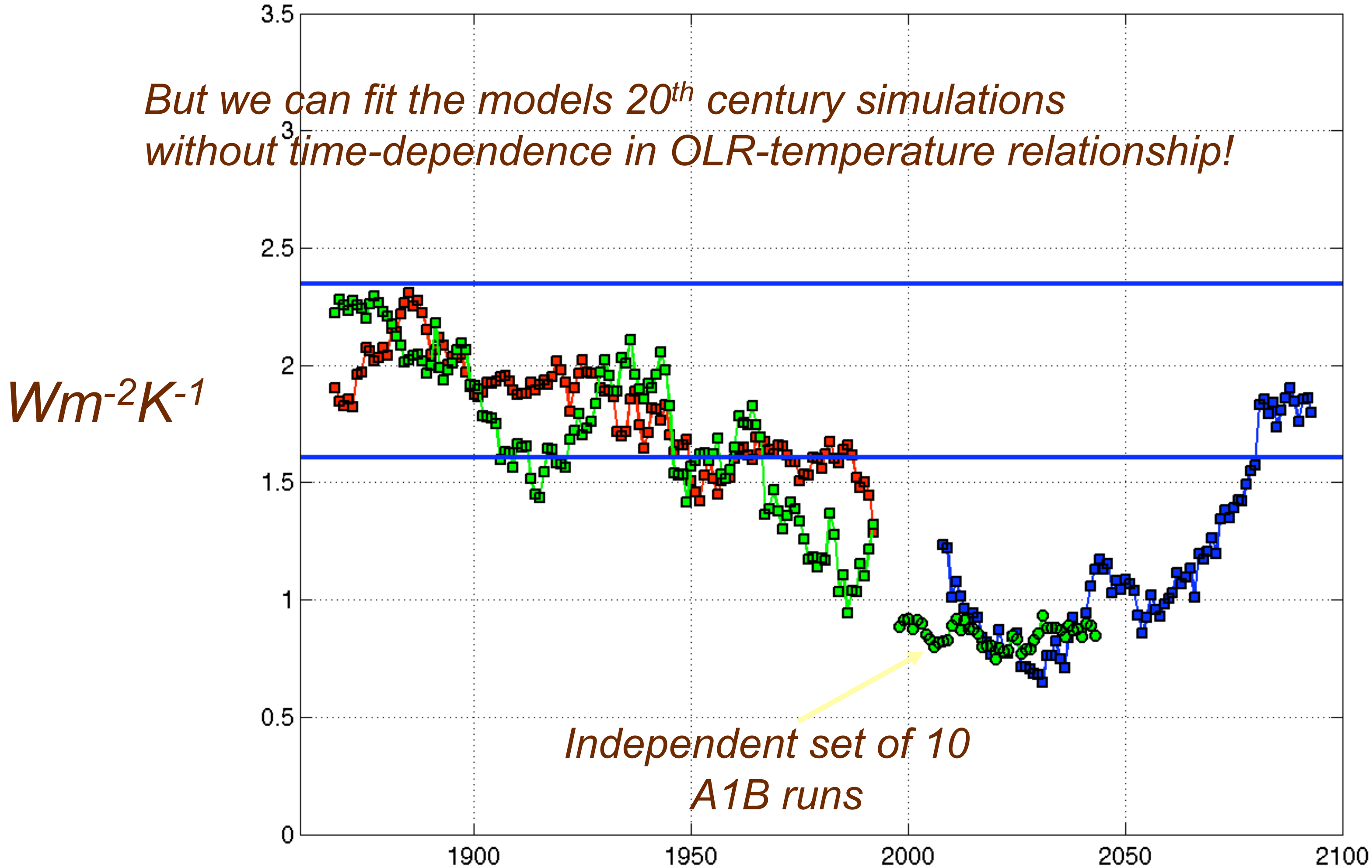
Longwave regression across ensemble, following K. Swanson 2008




Longwave regression across ensemble,
following K. Swanson 2008
Wm-2K-1
3.5
3
2.5
2
1.5
1
0.5
0
1900
1950
2000
2050
2100
Well-mixed
greenhouse gases only

Longwave regression across ensemble, following K. Swanson 2008

But we can fit the models 20th century simulations without time-dependence in OLR-temperature relationship!



May be telling us that ENSO is changing, but with no obvious connection to global sensitivity

A framework for inferring sensitivity from internal variability:
(why wait for a volcano when the climate is always relaxing back from being perturbed naturally

Fluctuation-dissipation
(Fluctuation-response)

$$dx/dt = Lx + N + F \qquad N = white \;\; noise$$

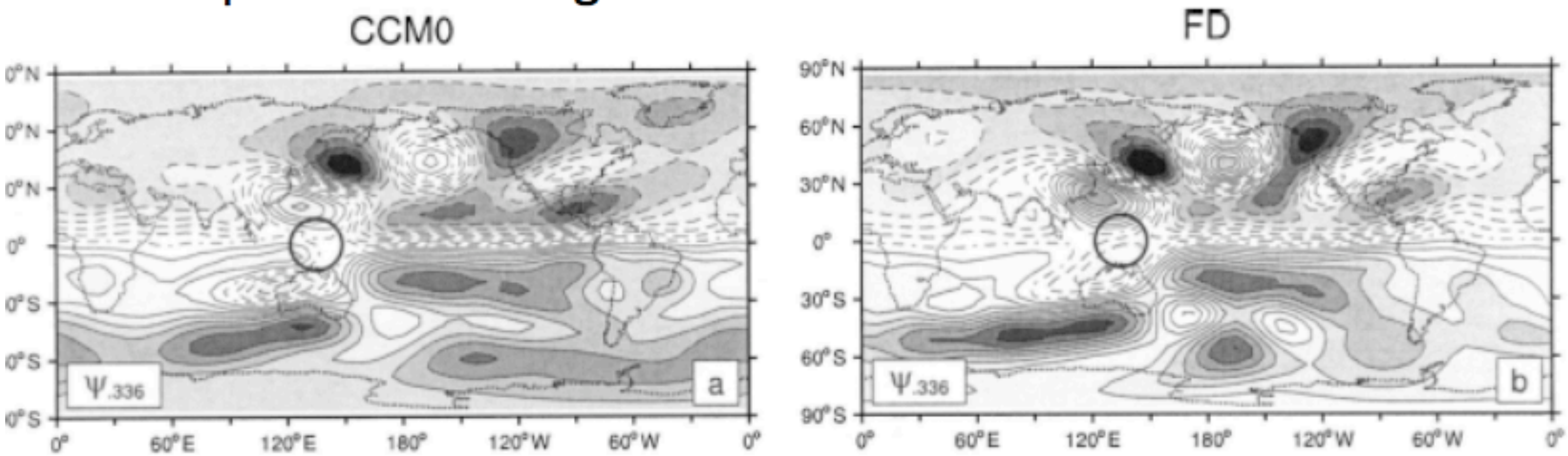
$$< x >= L^{-1}F$$

$$C(t) =< x_i(t)x_j(0) >; \qquad L^{-1} = \int_0^\infty C(t)C^{-1}(0)dt$$

Exact for this multi-variate linear system, but also works for some nonlinear systems – ie statistical mechanics

GCM response to localized equatorial heating

response obtained from fluctuation-dissipation relation



upper tropospheric streamfunction

Gritsun and Branstator, 2007

Final Thoughts:

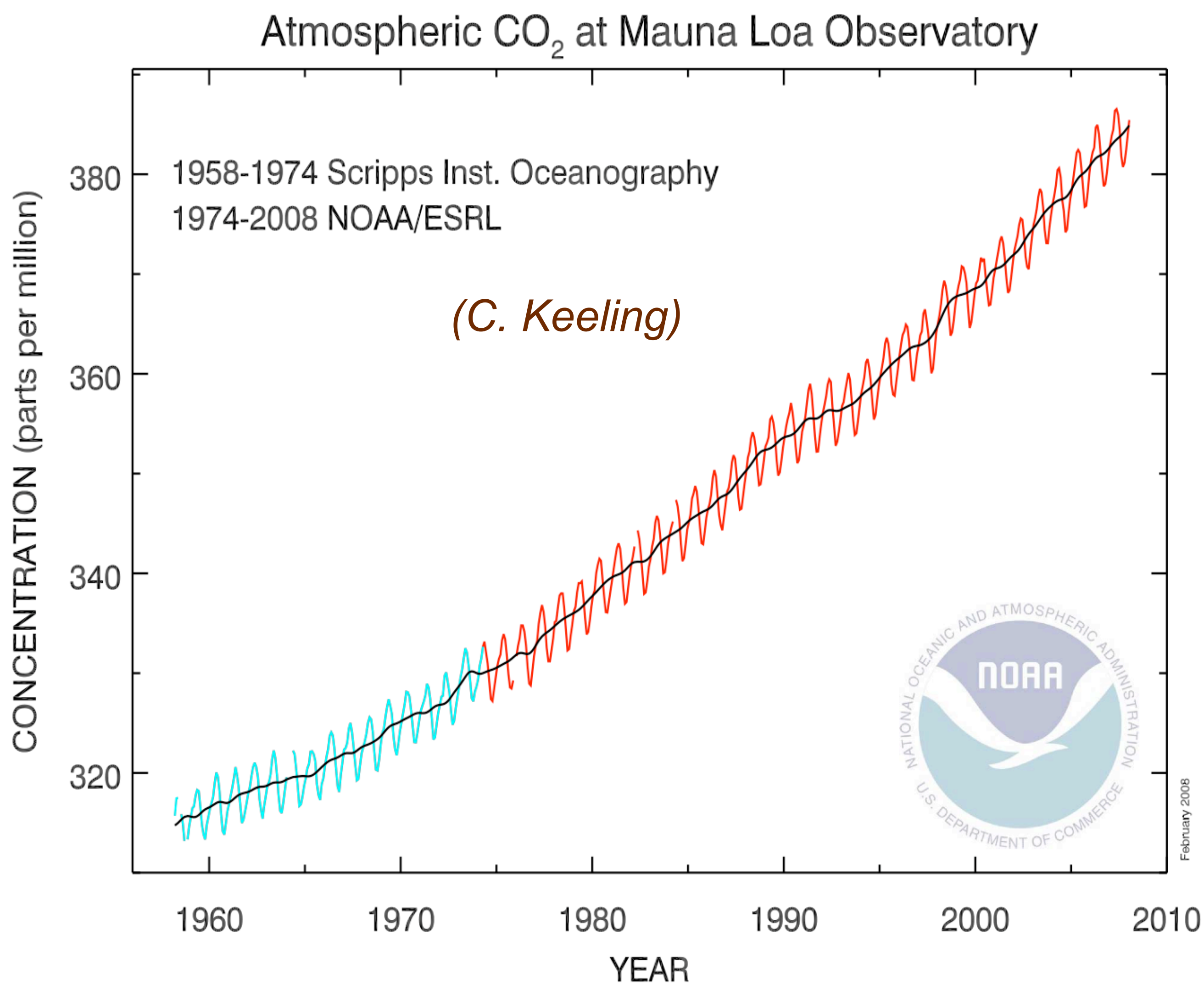
1) The uncertainty in forcing over the 20th century is what primarily limits our ability to use 20th century warming to determine transient sensitivity empirically
=> constraining aerosol forcing the key

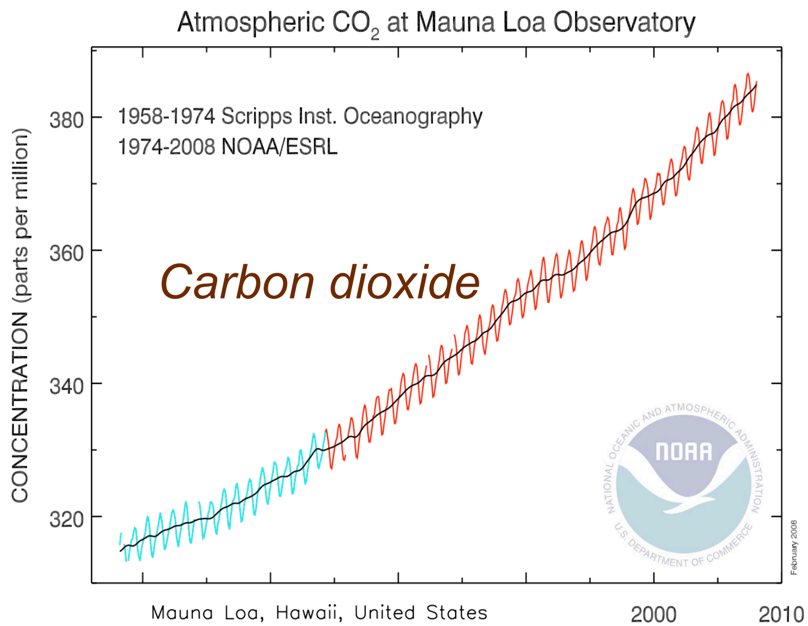
2) The difficulty in simulating clouds prevents us from developing a satisfying reductive theory/model of climate sensitivity
(Can we constrain cloud feedbacks analogously to how Hall and Qu constrain albedo feedbacks?)

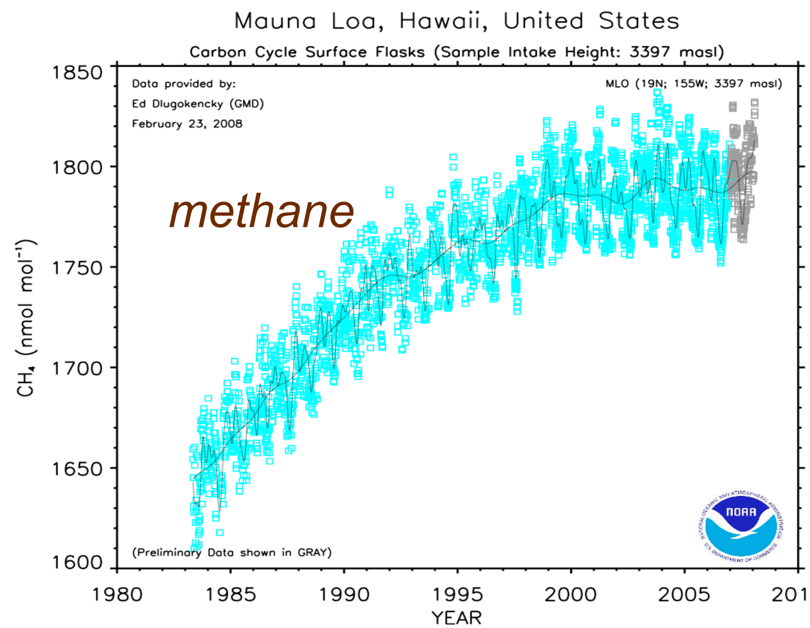
3) Is some of the spread in estimates of sensitivity based on different methods due to inappropriate simple models/concepts (e.g., ignoring the efficacy of heat uptake)?

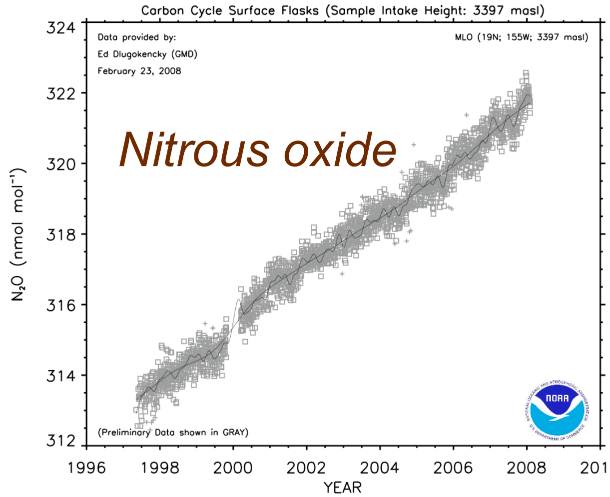
4) Can one use observations of internal variability (temporal correlations or relationships between TOA fluxes and other fields) to constrain sensitivity

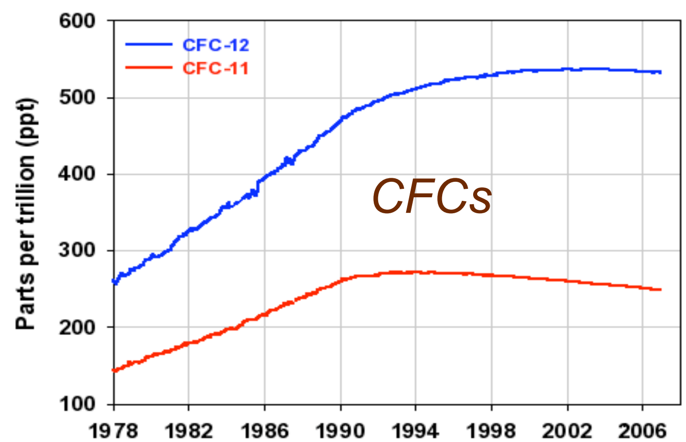
Supplementary figures


Atmospheric CO2 at Mauna Loa Observatory
1958-1974 Scripps Inst. Oceanography
1974-2008 NOAA/ESRL
(C. Keeling)
CONCENTRATION (parts per million)
380
360
340
320
1960
1970
1980
1990
2000
2010
YEAR
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE
February 2008



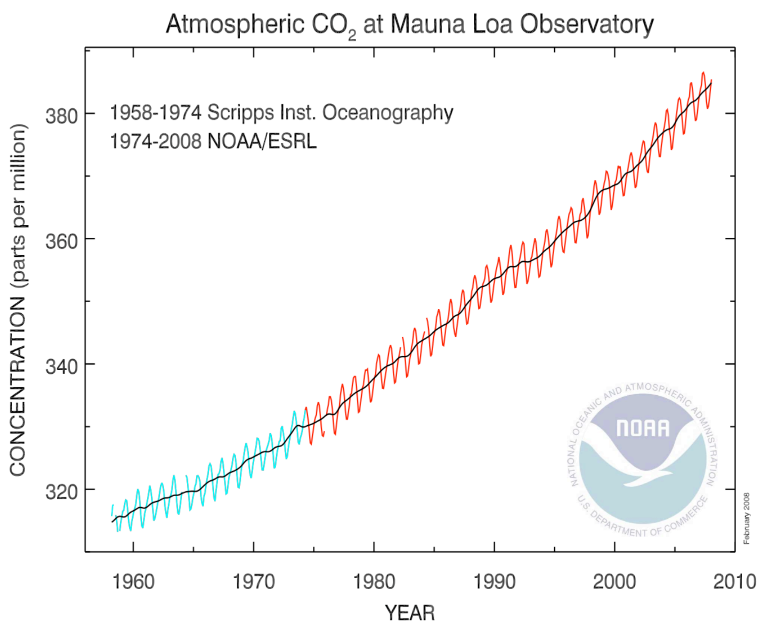






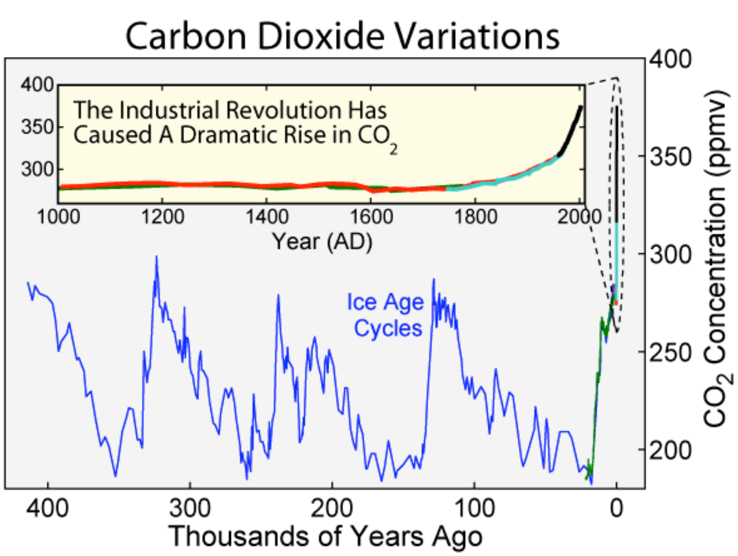
Methane and Nitrous Oxide: (1976) Wang, W.-C., et al
CFCs: (1975) V. Ramanathan

(1974) Molina-Rowland: catalytic destruction of ozone by chlorine;
(1985) Farman et al: ozone hole

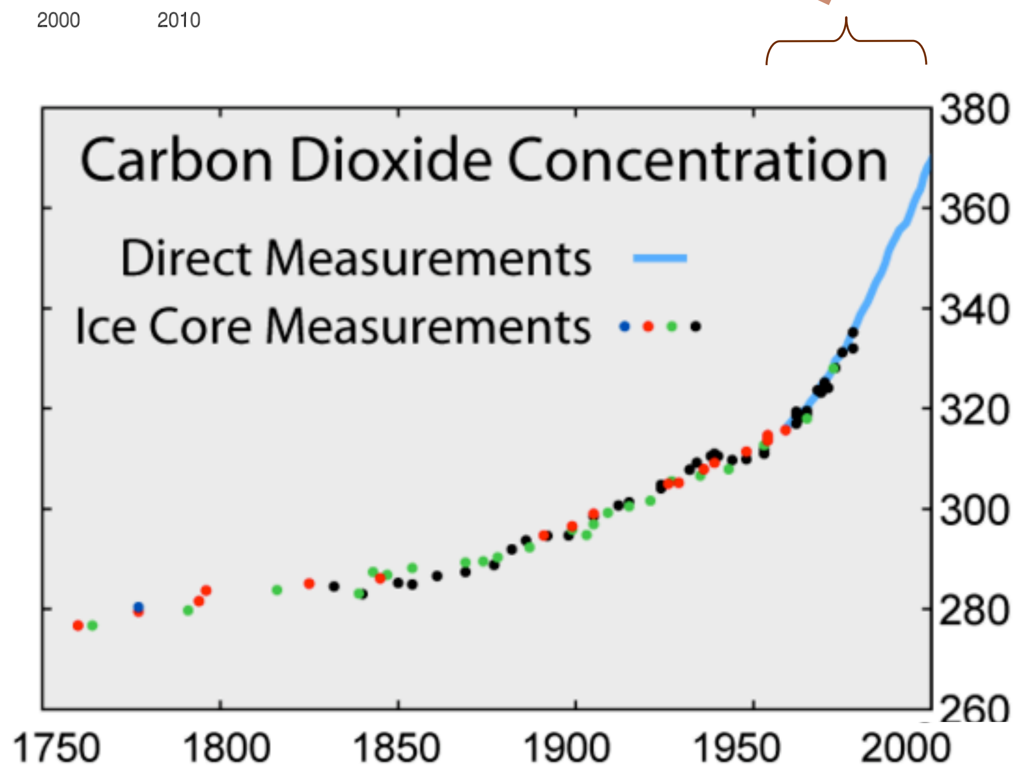


Ice cores + direct measurements provide a beautiful record of the history of atmospheric carbon dioxide

www.globalwarmingart.com.

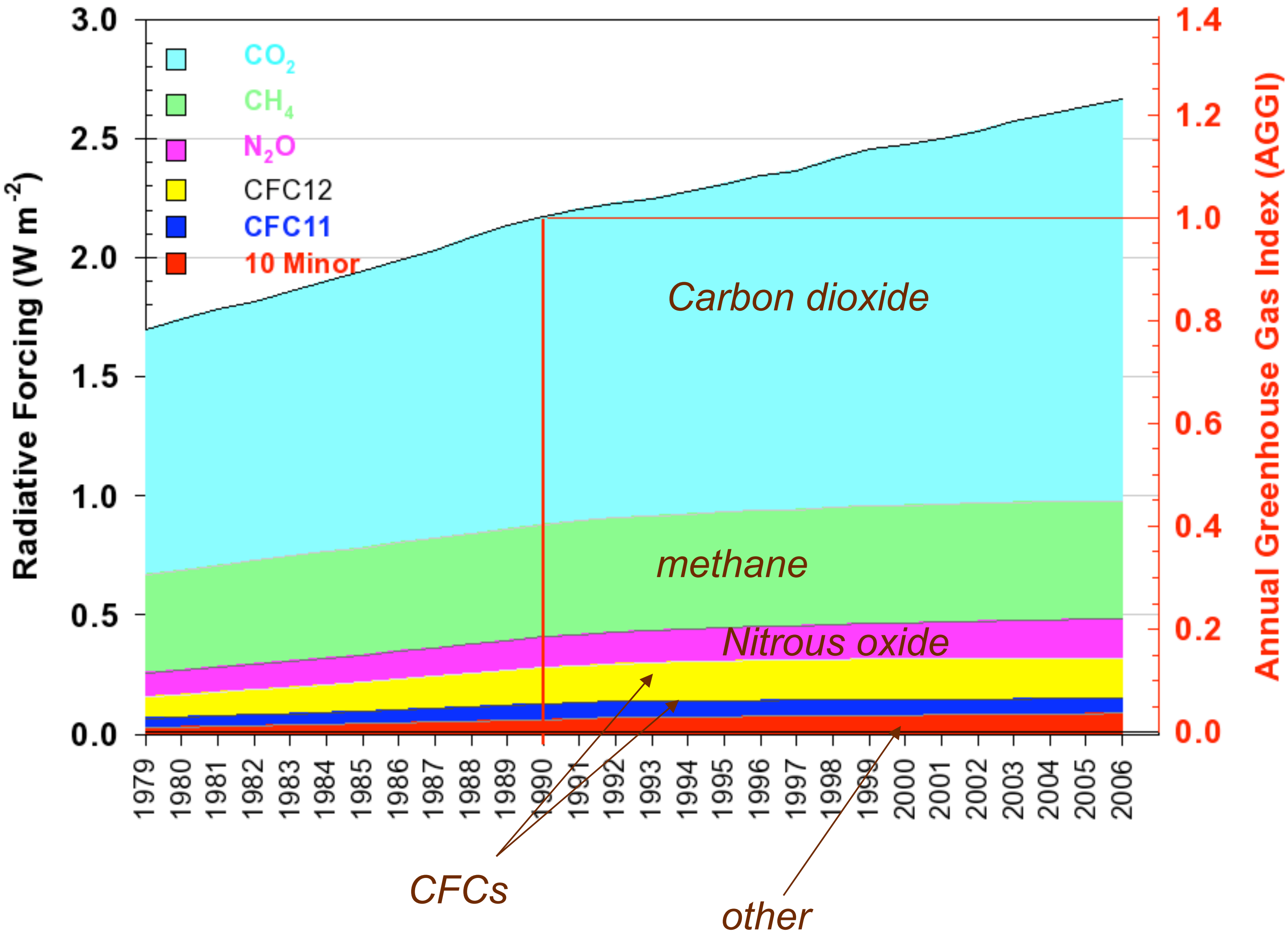


Jouzel, Lorius et al-- Vostok late 70's-80's



Etheridge, et al -- Law Dome 1990's

http://www.esrl.noaa.gov/gmd/aggi/



Was the 20th century warming

1) primarily forced by increasing greenhouse gases?

or,

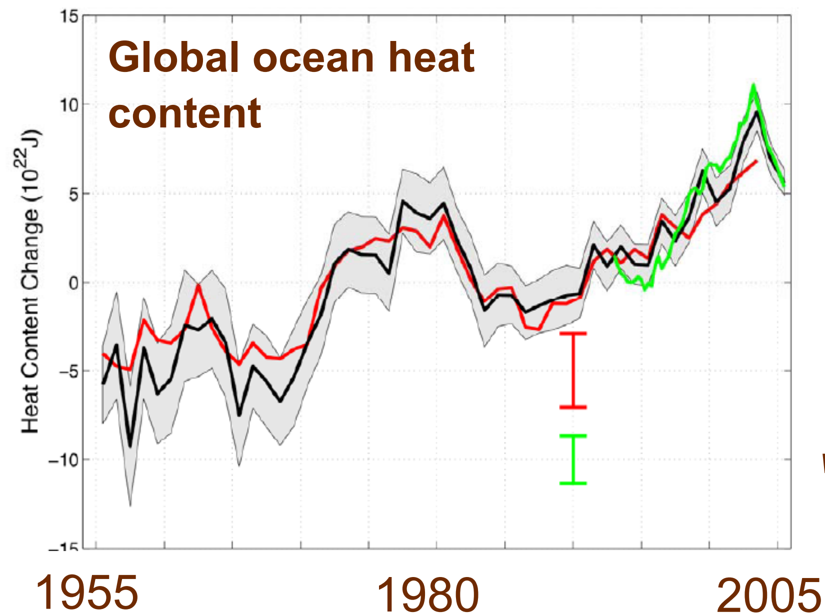
2) primarily forced by something else?

or,

3) primarily an internal fluctuation of the climate?

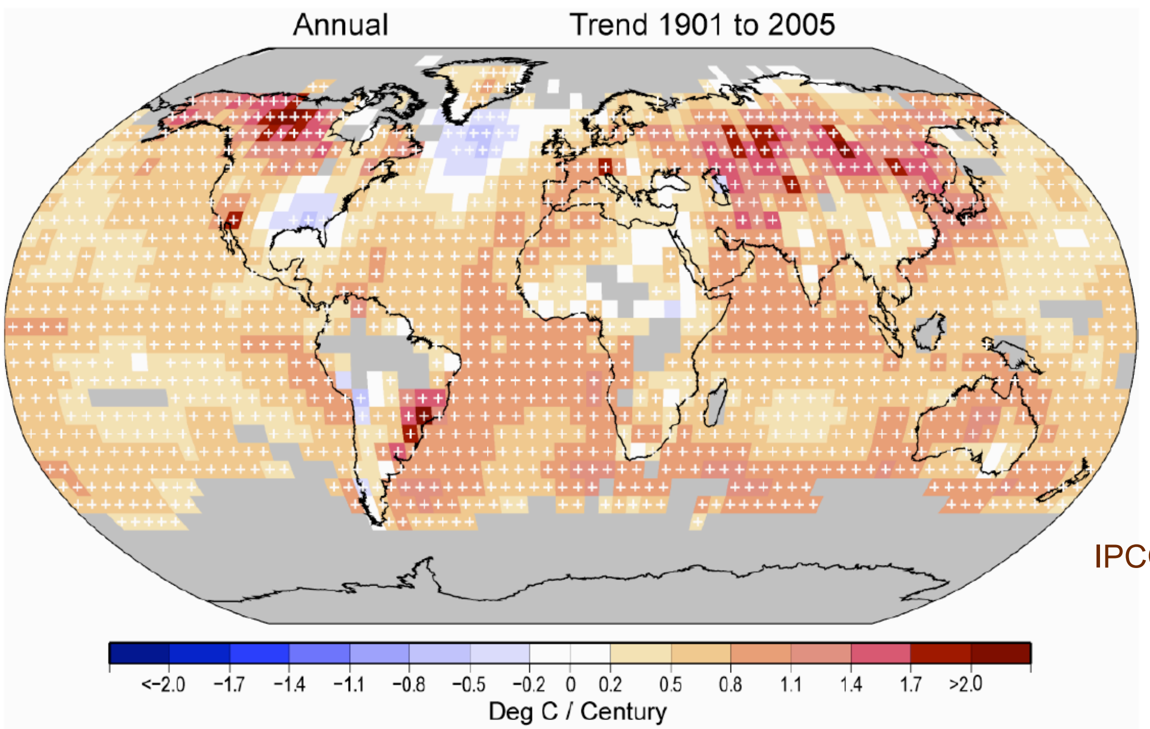
Claim: Our climate theories STRONGLY support 1)

A central problem for the IPCC has been to evaluate this claim and communicate our level of confidence appropriately



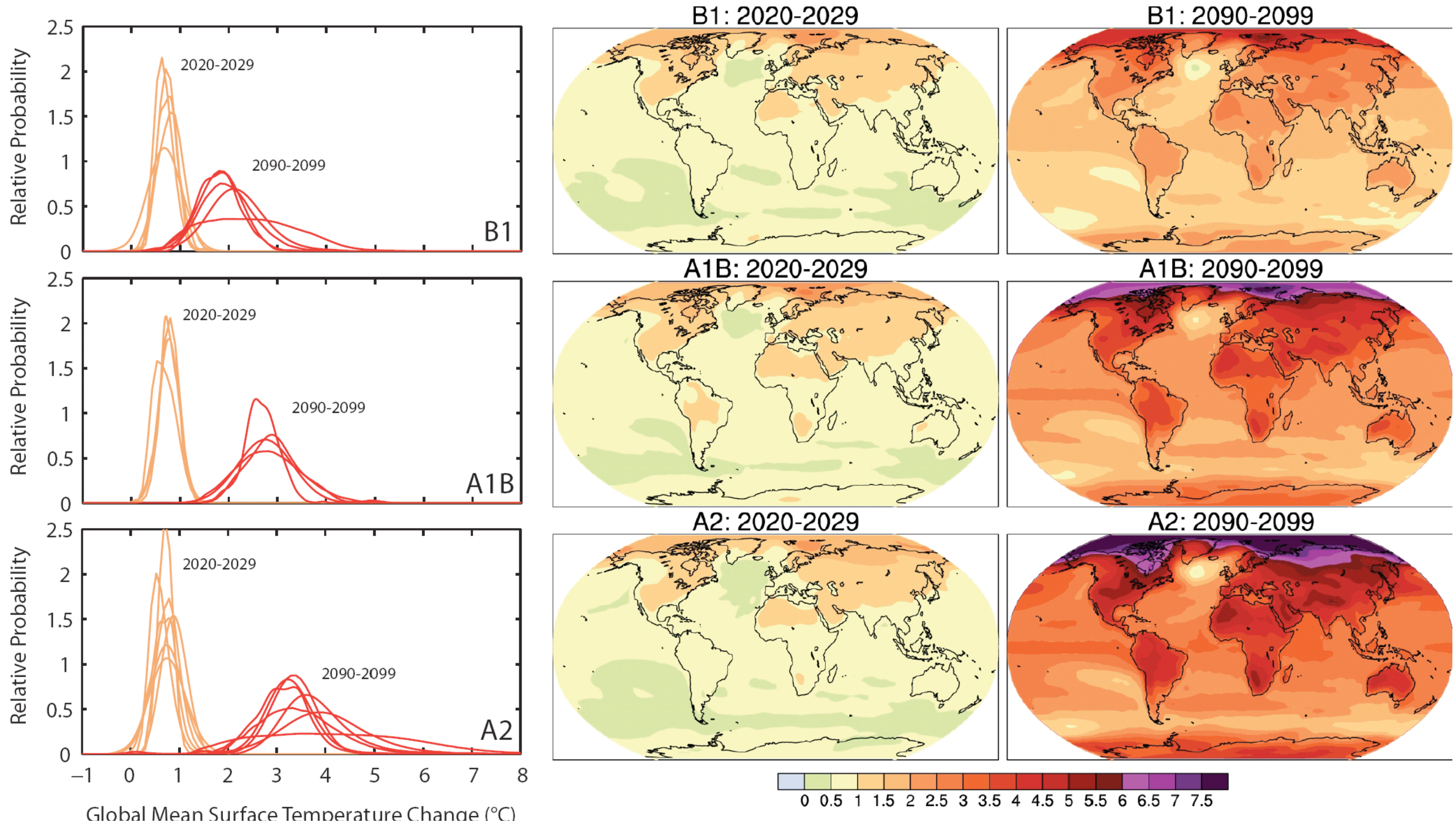
Energy is going into ocean
=>
More energy is entering the atmosphere from space than is going out

www.globalwarmingart.com

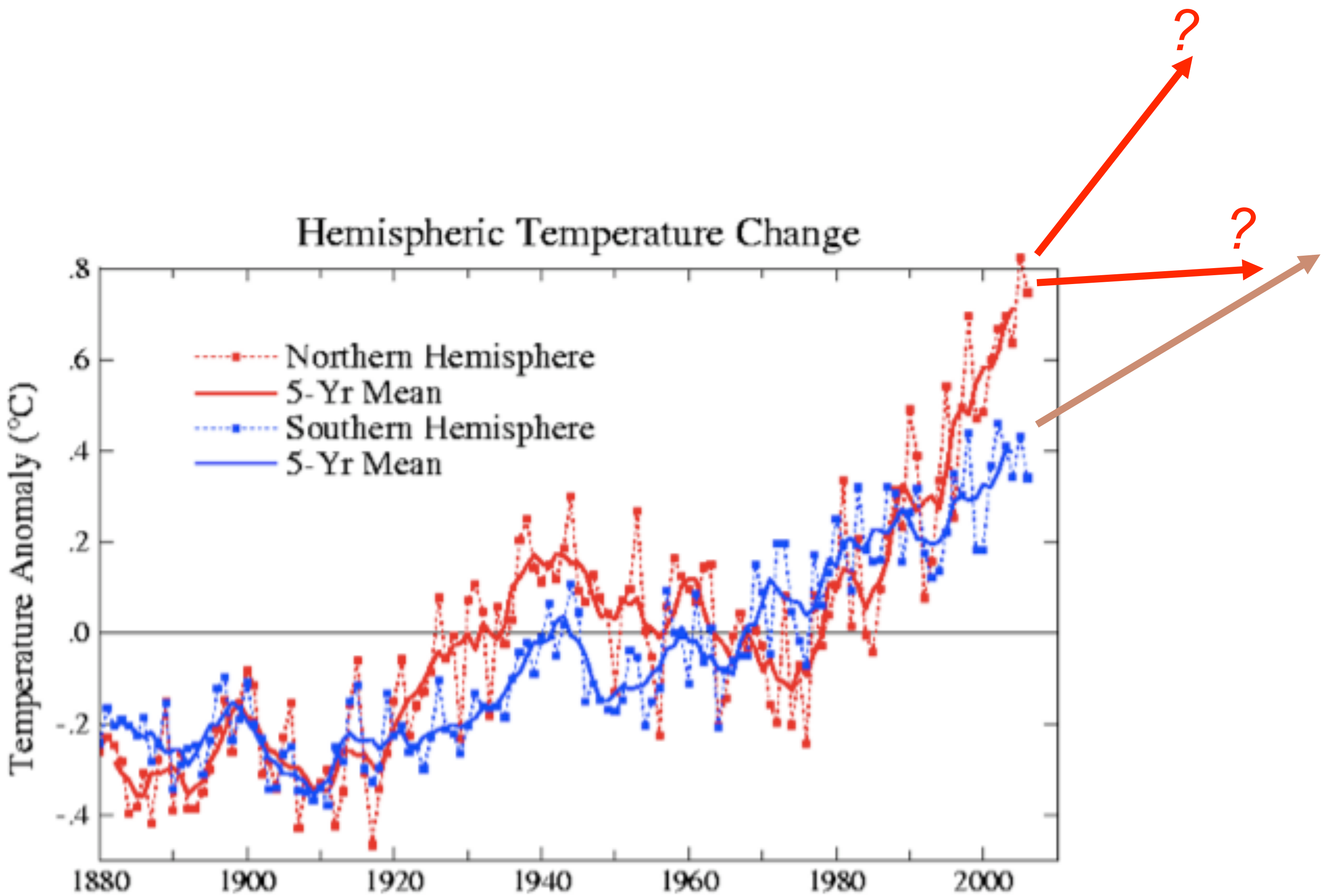


Almost all parts of the Earth's surface have warmed over the past 100 years

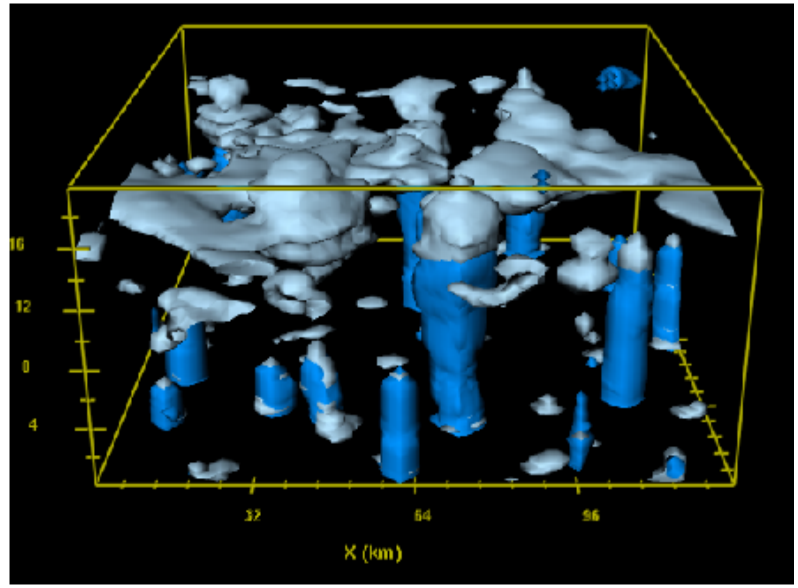
IPCC 4th Assessment Report.



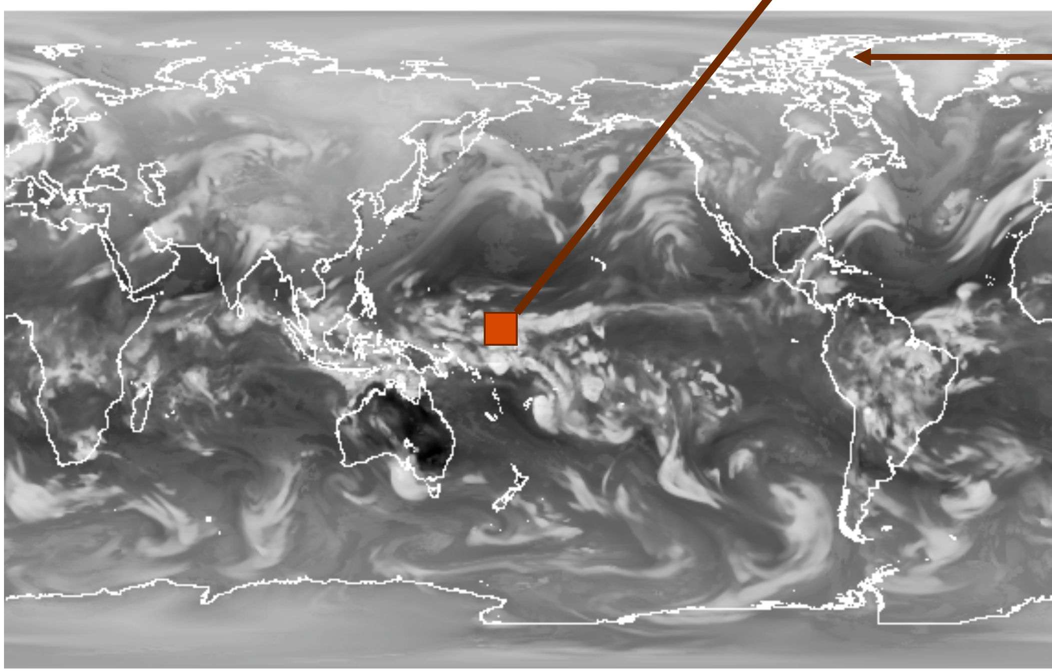
IPCC AR4 WG1 Summary for Policymakers


Hemispheric Temperature Change
Northern Hemisphere
5-Yr Mean
Southern Hemisphere
5-Yr Mean
Temperature Anomaly (°C)
.8
.6
.4
.2
.0
-.2
-.4
1880
1900
1920
1940
1960
1980
2000
?
?

Clouds (especially in the tropics) are influenced by small scales in the atmospheric circulation

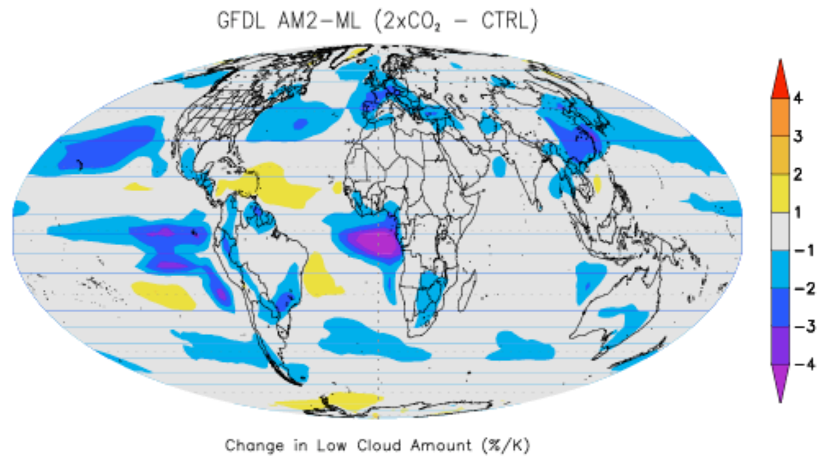


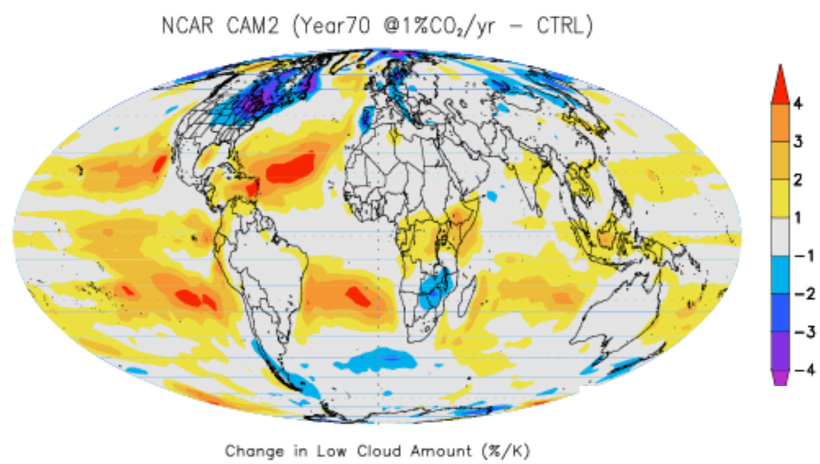
100kms



simulation of a 100km x 100km area of the tropics

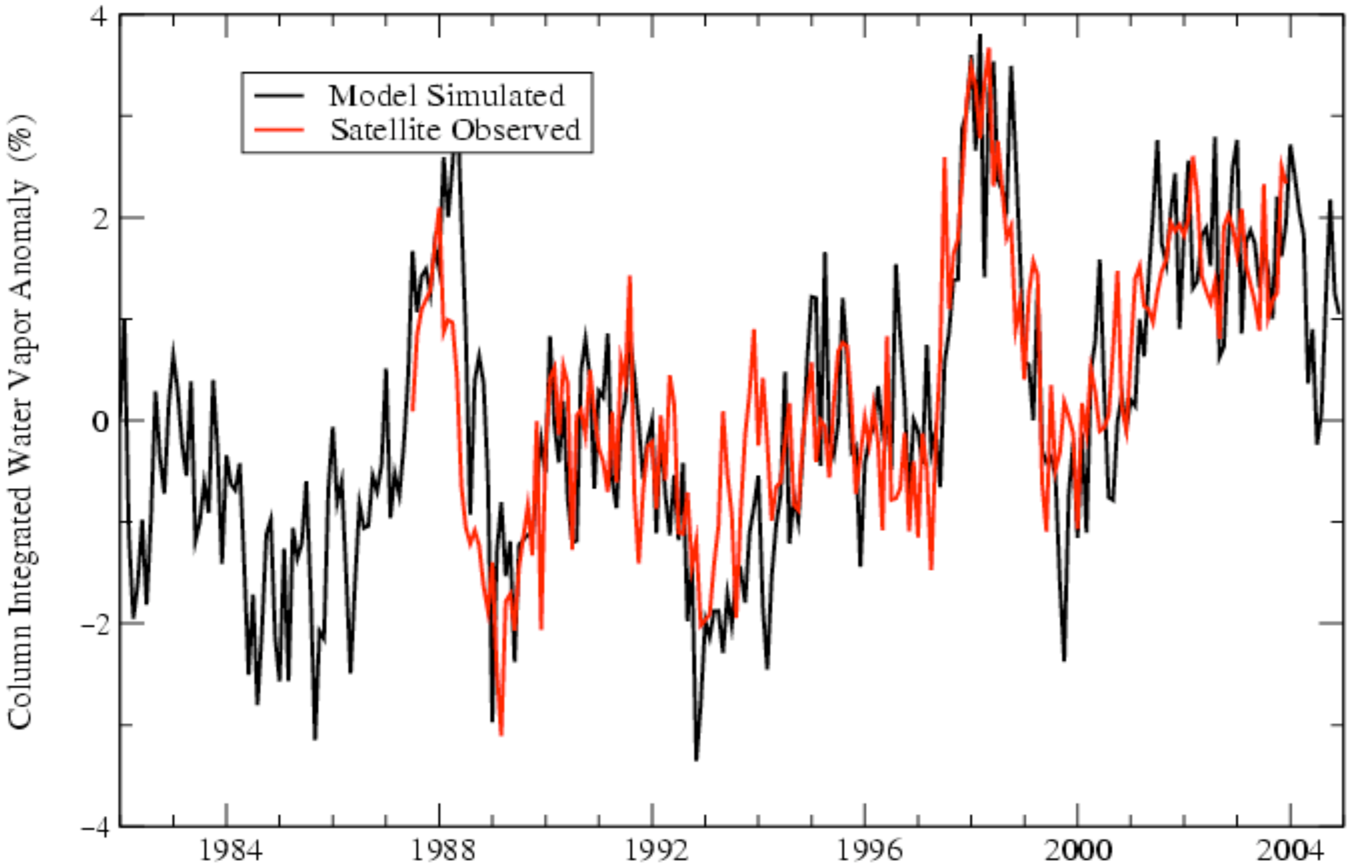
Change in Low Cloud Amount (%/K) GFDL and NCAR/CAM models





Courtesy of Brian Soden

Total Column Water Vapor Anomalies (1987-2004)



We have high confidence in the model projections of increased water vapor.

Held and Soden J.Clim. 2006