AEROSOLS AND CLIMATE SENSITIVITY

John A. Ogren
NOAA Earth System Research Laboratory
Boulder, Colorado, USA

seminar presented at
National Central University
Chung-li, Taiwan
August 24, 2009

- What is climate sensitivity?
  - ❖ proportionality "constant" relating climate response and climate forcing
- I thought this was going to be an aerosol talk. Why is an aerosol guy talking about climate sensitivity?
  - ❖ I wonder about that too!
  - ❖ Climate sensitivity is not my expertise, but it is a crucial motivation for our research (including at Lulin Mountain).
- Special thanks to Steve Schwartz for dragging me into this.

WHY HASN'T EARTH WARMED AS MUCH AS EXPECTED?

Stephen E. Schwartz

BROOKHAVEN NATIONAL LABORATORY

Robert J. Charlson, Ralph A. Kahn, John A. Ogren & Henning Rodhe

Gordon Research Conferences

Radiation & Climate

Colby-Sawyer College
New London, NH
July 5-10, 2009

http://www.ecd.bnl.gov/steve

WHY HASN'T EARTH WARMED AS MUCH AS EXPECTED. . .

FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

THE WARMING DISCREPANCY

IPCC recommends a climate sensitivity of 3°C (2–4.5°C) warming for a doubling of CO_2.

The radiative forcing (i.e., additional energy trapped) caused by CO_2 doubling is 3.7 W m^{-2}.

The preindustrial to present (year 2005) GHGs forcing is 3 (2.6 to 3.5) W m^{-2}.

It then follows that the expected warming caused by the 3 W m^{-2} forcing is 2.4°C (1.4–4.3°C).

If the only anthropogenic climate forcing on the planet is caused by the build-up of GHGs, and even if we prevent further increases in the GHGs beyond their 2005 levels, the planetary warming (since the preindustrial era) would reach 2.4°C (1.4 – 4.3°C).

Why have we not seen this large warming?

Ramanathan and Feng, PNAS, 2008

WHY HASN'T EARTH WARMED AS MUCH AS EXPECTED. . .

FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

- Uncertainty in greenhouse gas forcing.
- Countervailing natural cooling over the industrial period.
- Lag in reaching thermal equilibrium.
- Countervailing cooling forcing by aerosols.
- Climate sensitivity lower than current estimates.

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Implications

Path forward

HOW MUCH WARMING IS EXPECTED?

$$\begin{array}{c}\text{Equilibrium change}\\ \text{in global mean}\\ \text{surface temperature}\end{array} = \begin{array}{c}\text{Climate}\\ \text{sensitivity}\end{array} \times \text{Forcing}$$

$$\Delta T = S \times F$$

S is ***equilibrium*** sensitivity. Units: K/(W m^{-2})

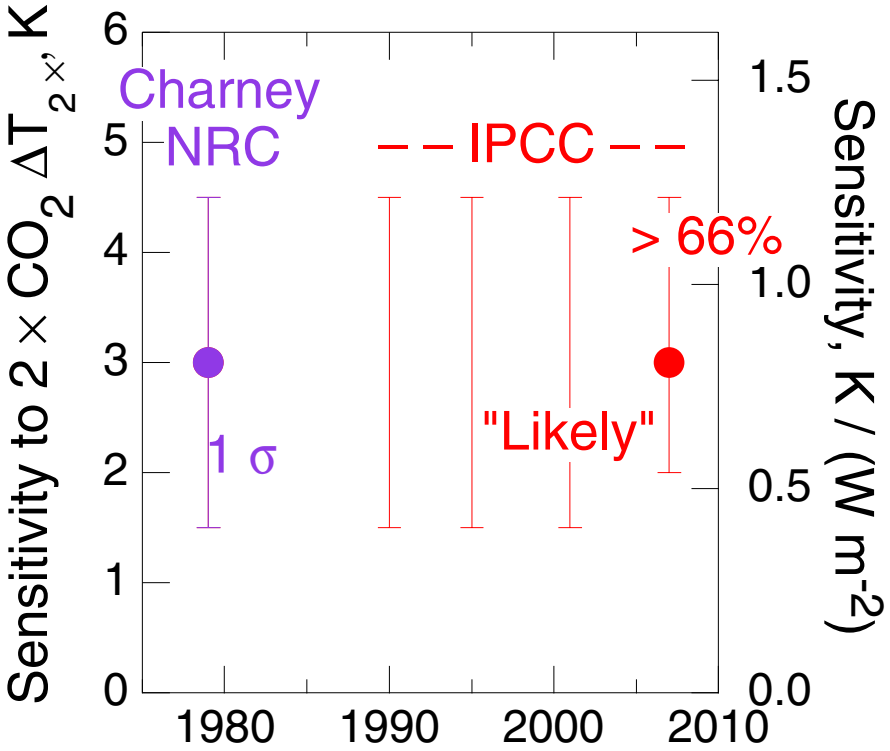
Sensitivity is commonly expressed as "CO_2 doubling temperature"

$$\Delta T_{2\times} \equiv S \times F_{2\times}$$

where $F_{2\times}$ is the CO_2 doubling forcing, *ca.* 3.7 W m^{-2}.

ESTIMATES OF EARTH'S CLIMATE SENSITIVITY AND ASSOCIATED UNCERTAINTY

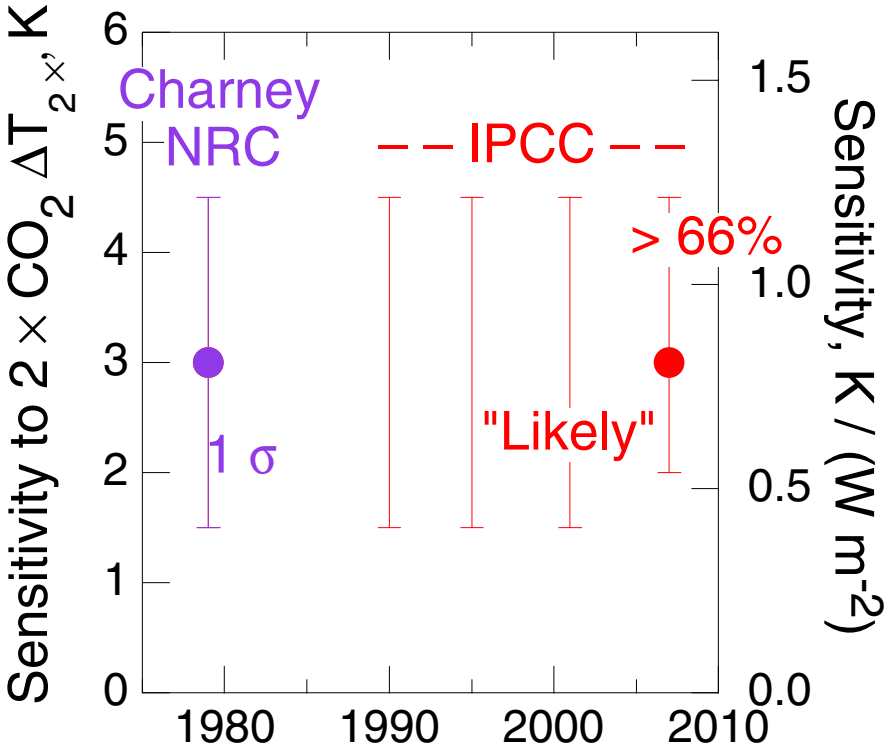
Major national and international assessments

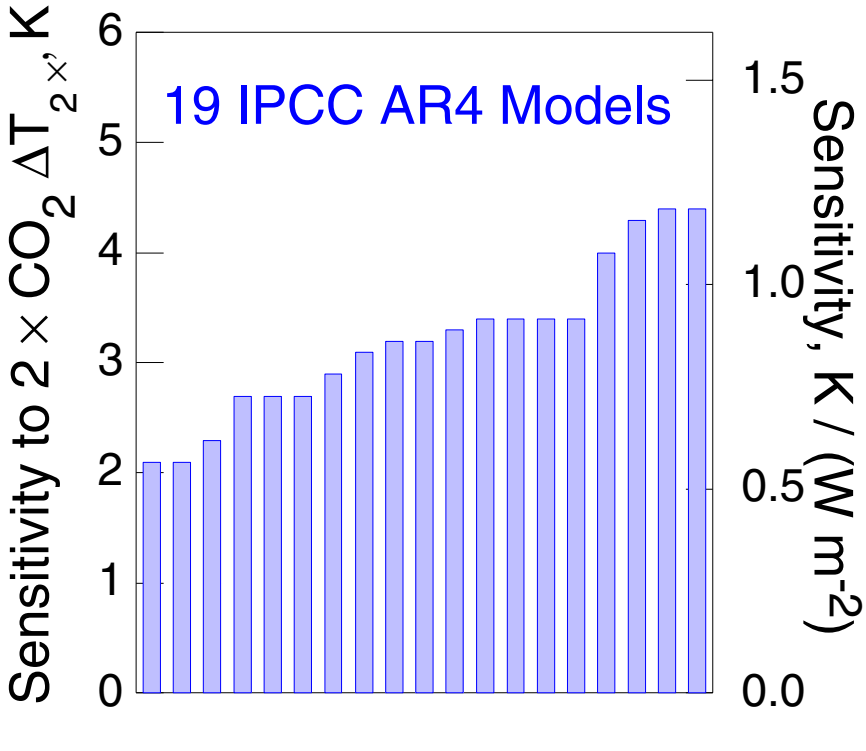


Current estimates of Earth's climate sensitivity are centered about a CO_2 doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty.

ESTIMATES OF EARTH'S CLIMATE SENSITIVITY AND ASSOCIATED UNCERTAINTY

Major national and international assessments and current climate models



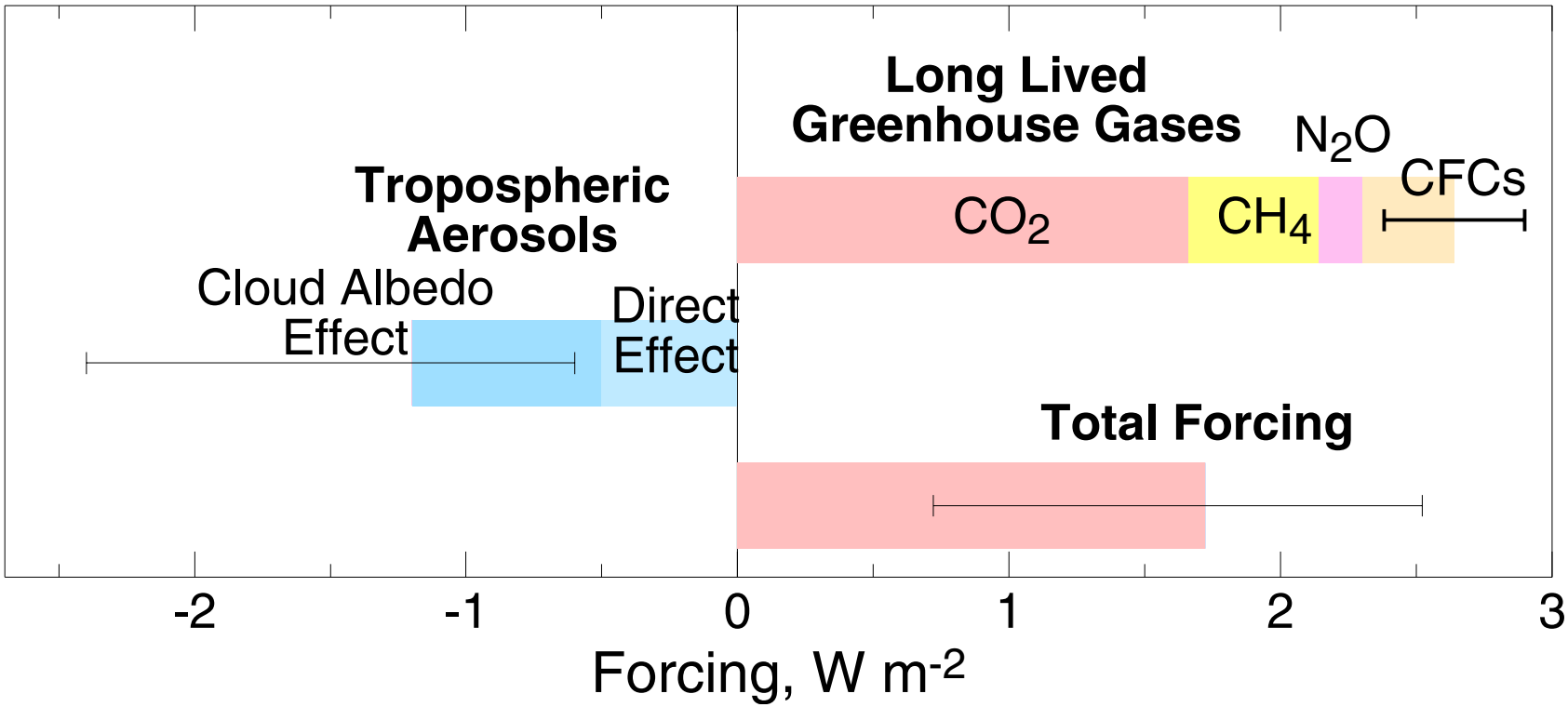


Current estimates of Earth's climate sensitivity are centered about a CO_2 doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty.

Range of sensitivities of current models roughly coincides with IPCC "likely" range.

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)



Total forcing includes other anthropogenic and natural (solar) forcings.

Forcing by tropospheric ozone, ~0.35 W m^{-2}, is the greatest of these.

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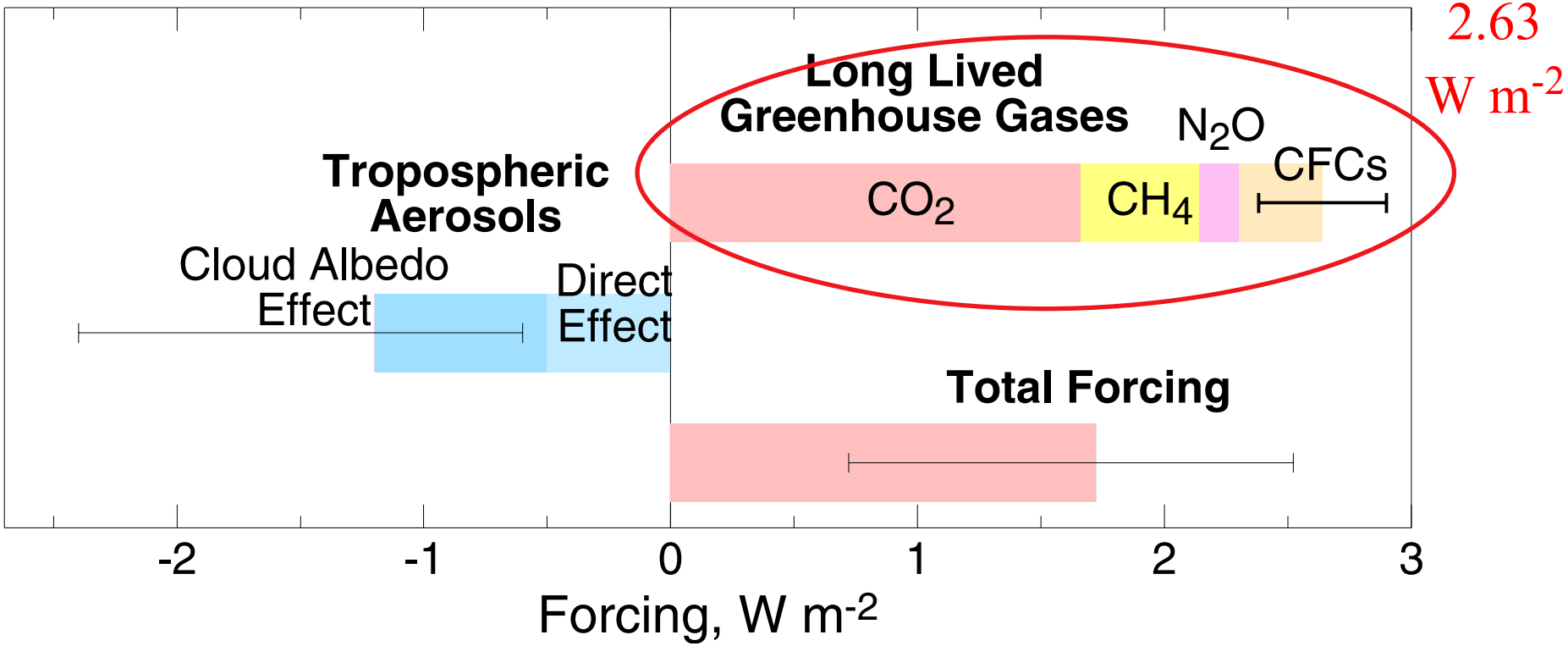

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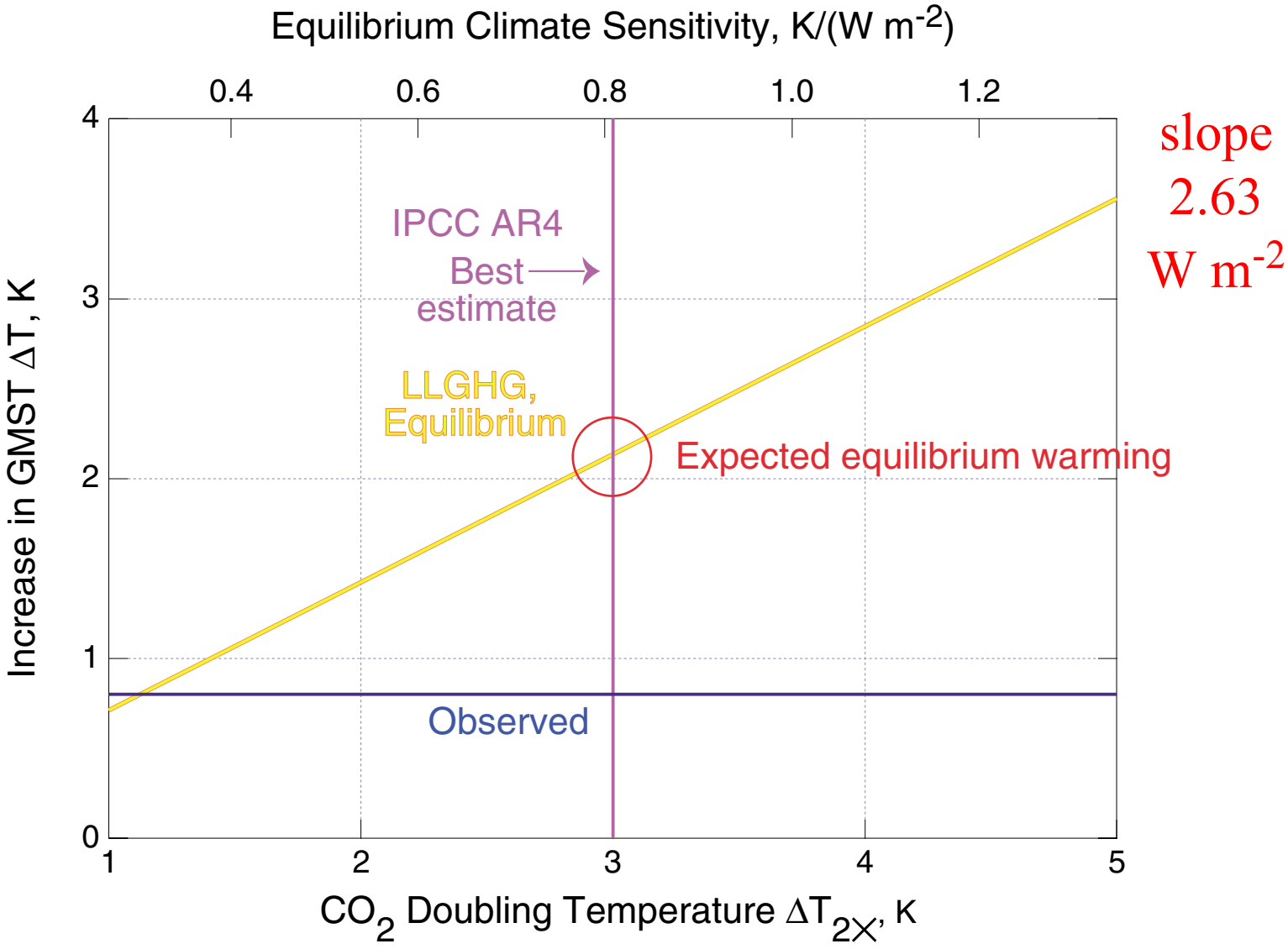
EXPECTED INCREASE IN GLOBAL TEMPERATURE

Long-lived GHGs only – Dependence on climate sensitivity



Observed increase in temperature is ***less than 40%*** of that expected for AR4 best-estimate sensitivity.

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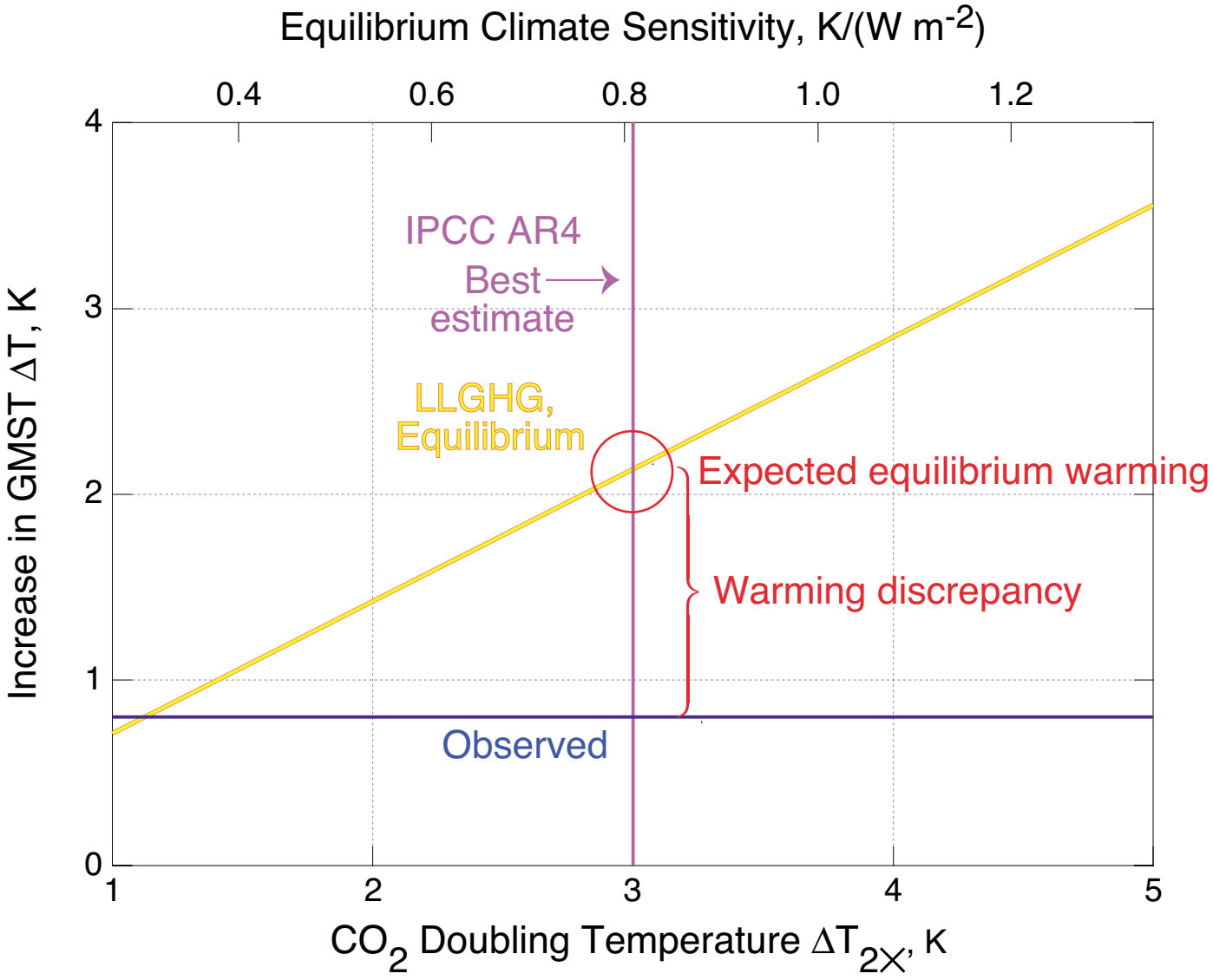

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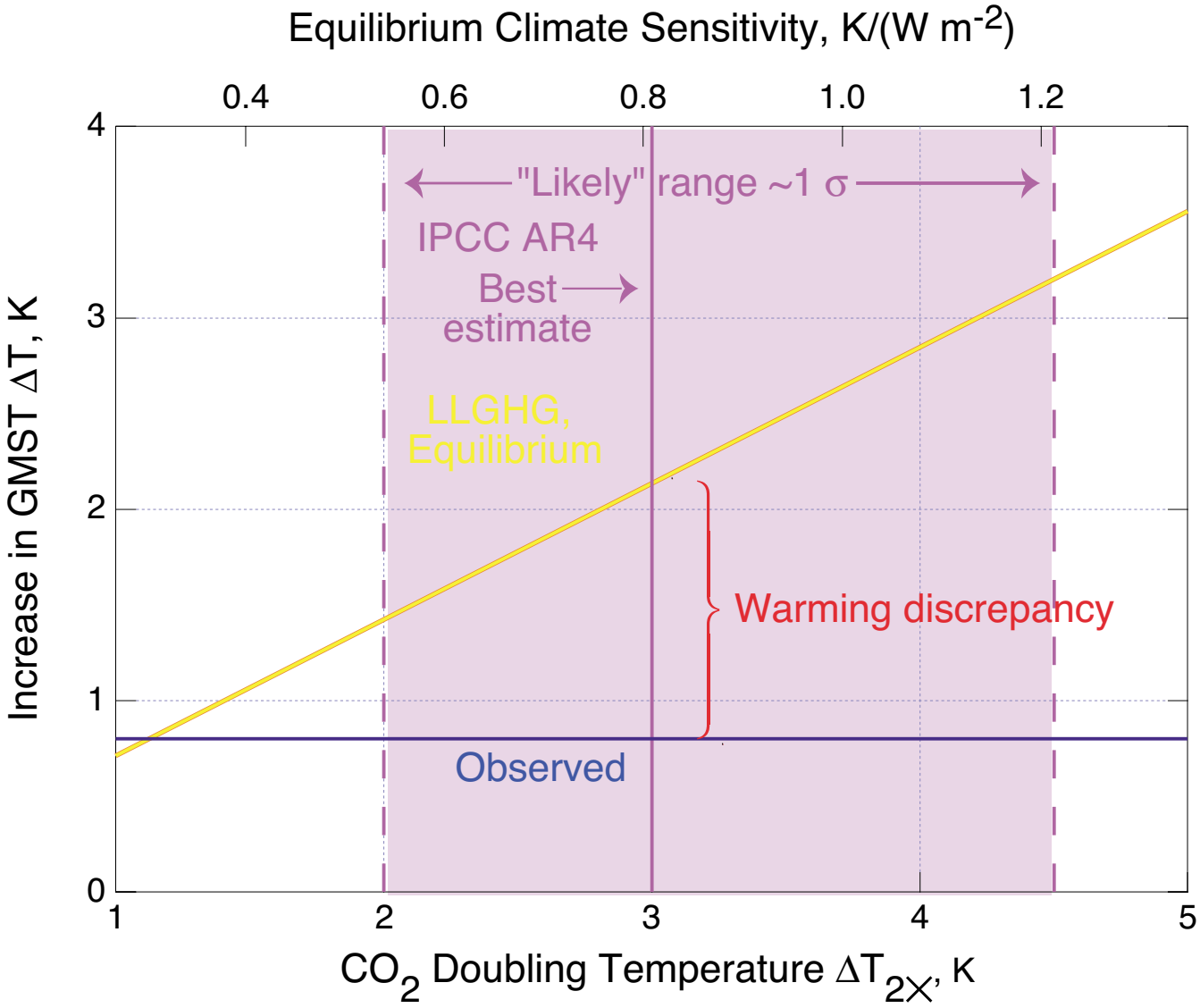

Ramanathan, PNAS 2008

This discrepancy holds throughout the IPCC AR4 "likely" range for climate sensitivity.

UNCERTAINTY IN GREENHOUSE GAS FORCING

UNCERTAINTY IN GREENHOUSE GAS FORCING

± 10%, 2 σ – IPCC

EXPECTED INCREASE IN GLOBAL TEMPERATURE

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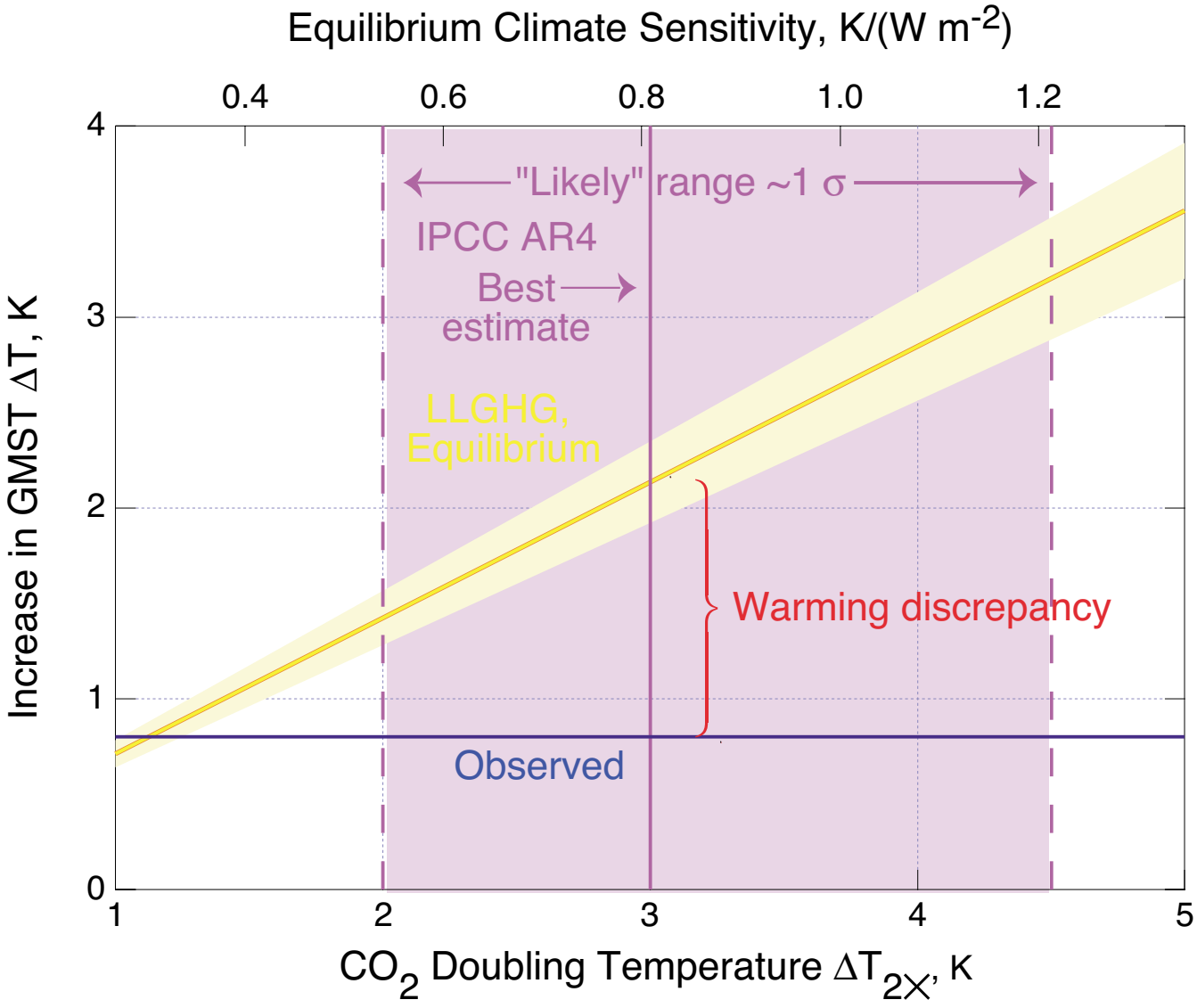


Collins, JGR 2006

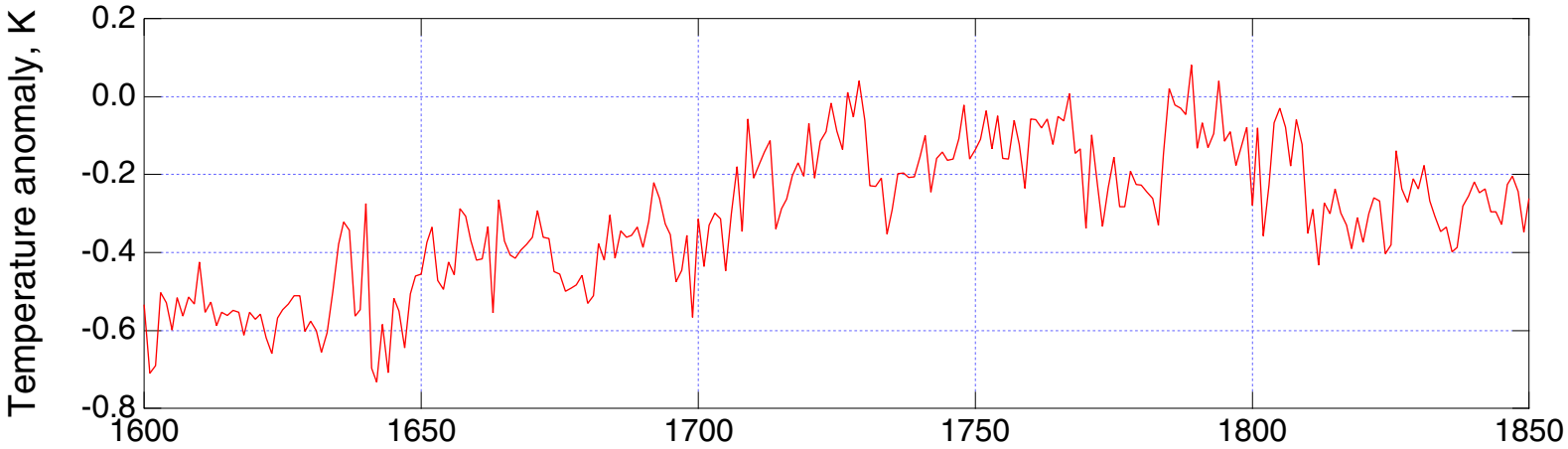
Gregory Webb JClim 2008

Little of the warming discrepancy is resolved by uncertainty in GHG forcing.

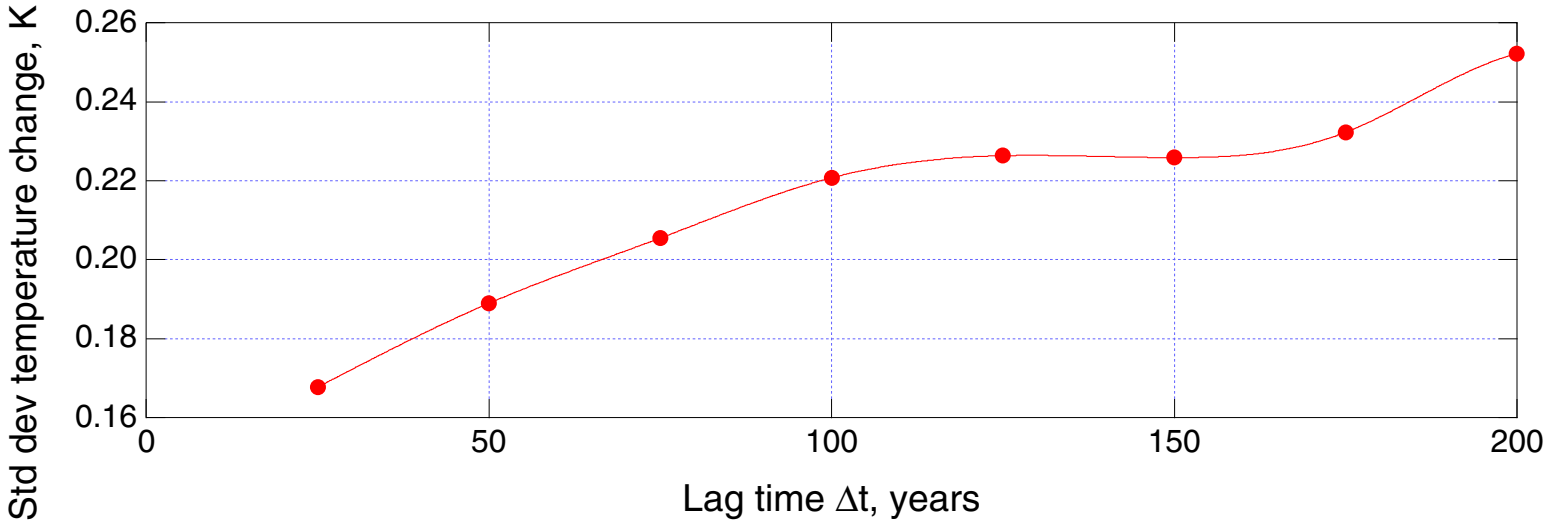
COUNTERVAILING NATURAL COOLING OFFSETTING EXPECTED WARMING

ESTIMATING NATURAL VARIABILITY

"Union" reconstruction of paleo temperature from ice cores, sediments, tree rings, corals



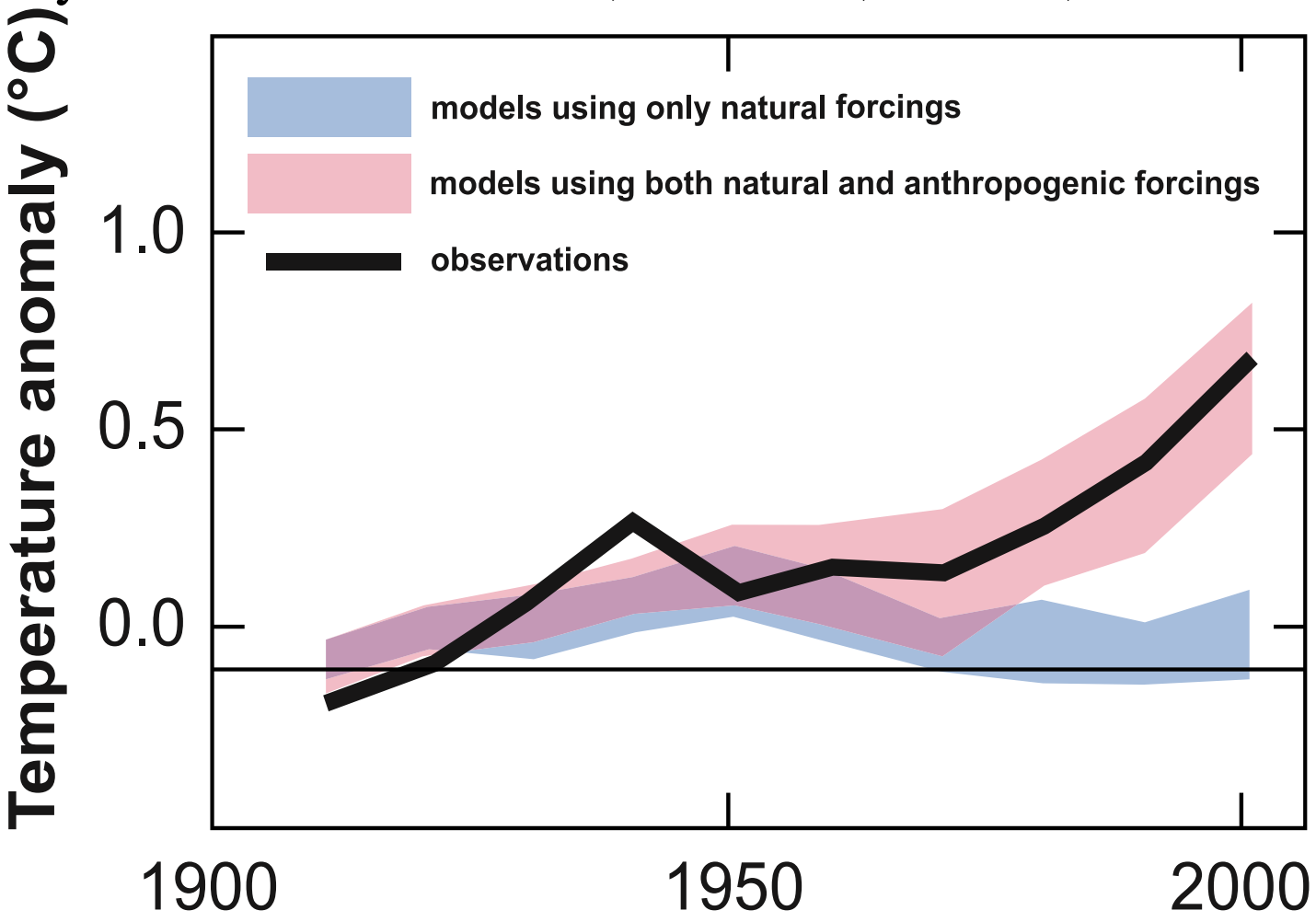
Juckes et al., Climate of the Past, 2007



Typical variation in temperature over 150 years ~ 0.2 K.

ESTIMATING NATURAL VARIABILITY

Anomaly relative to 1901-1950; 5 Models, 19 runs, from IPCC AR4



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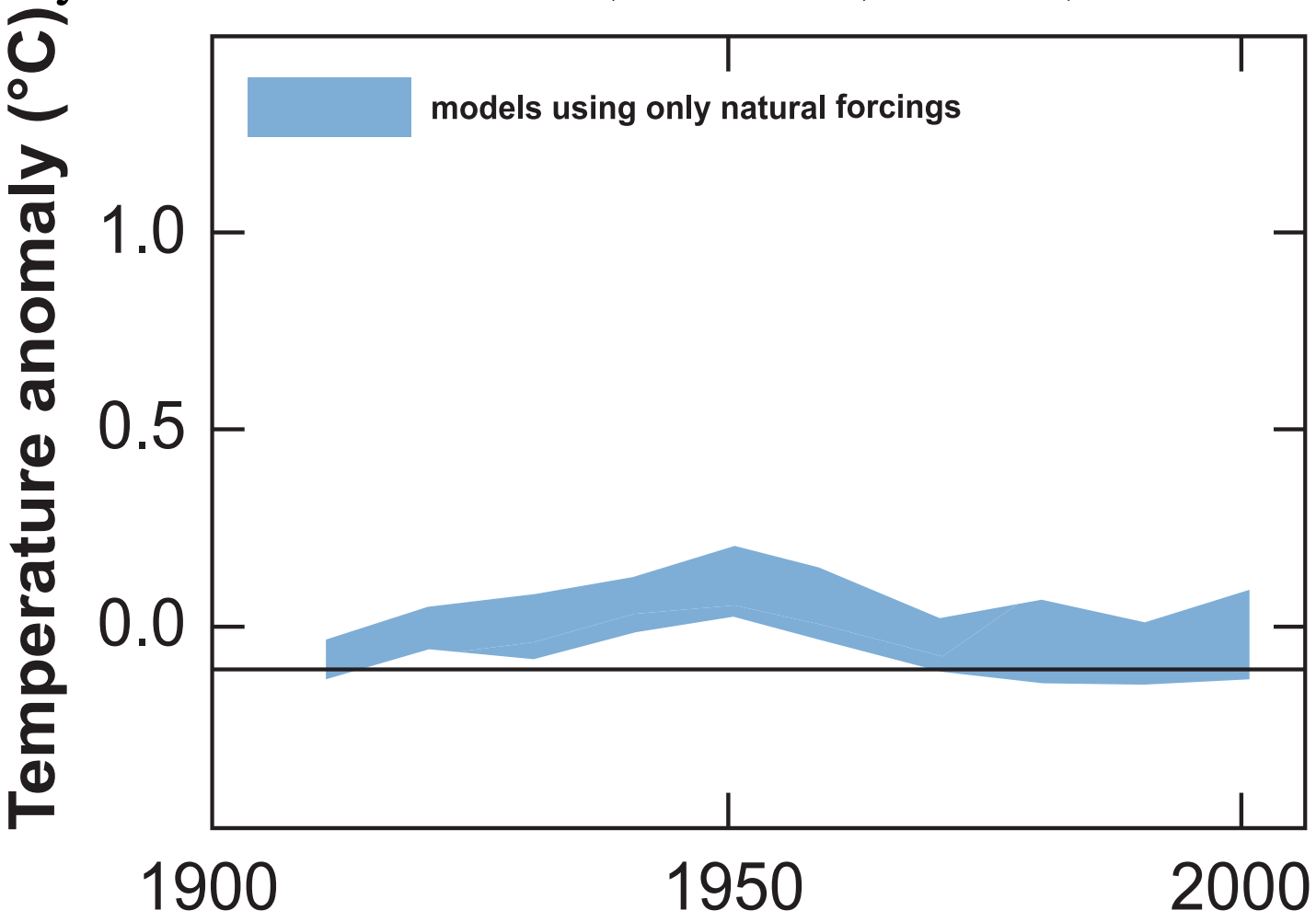

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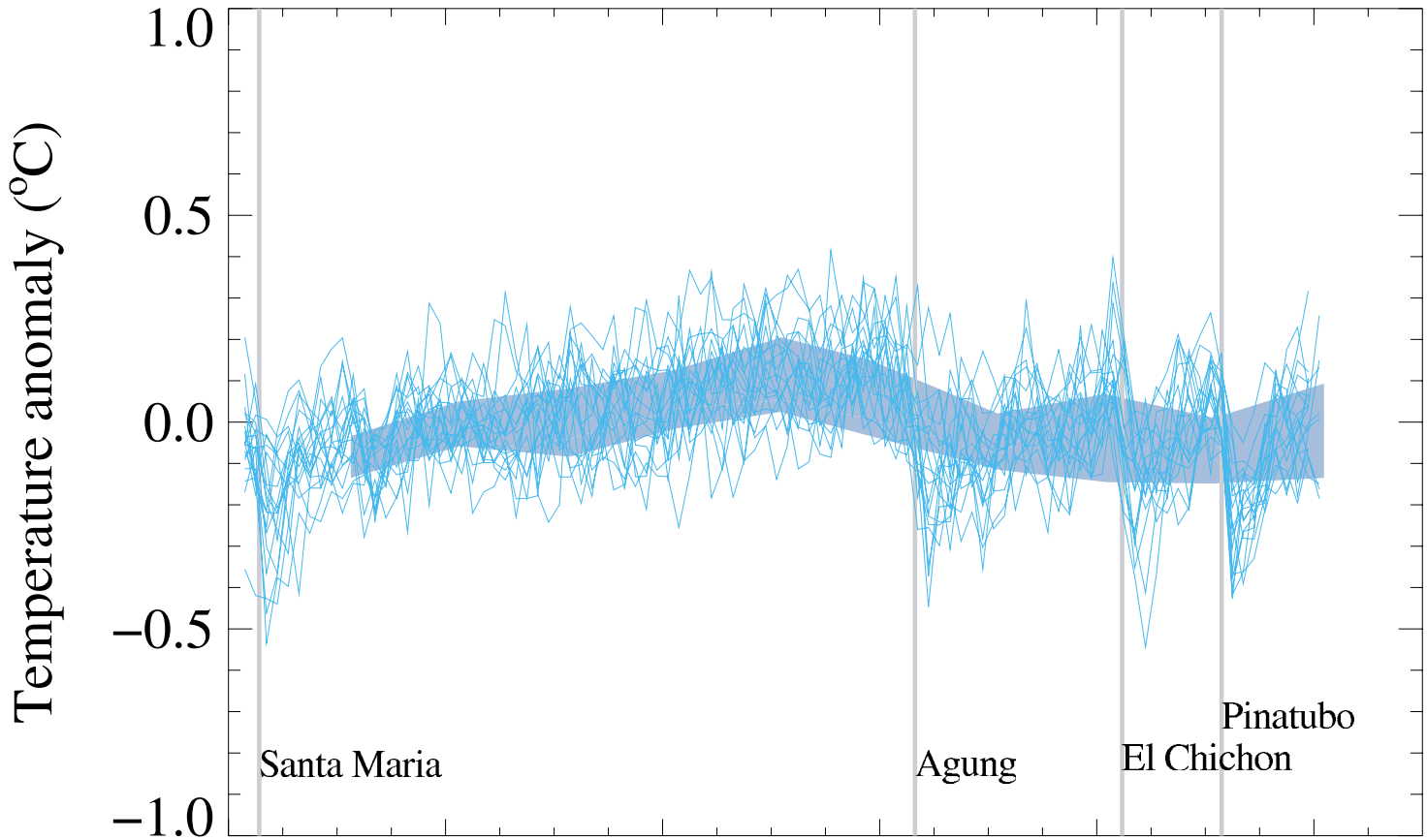

IPCC AR4

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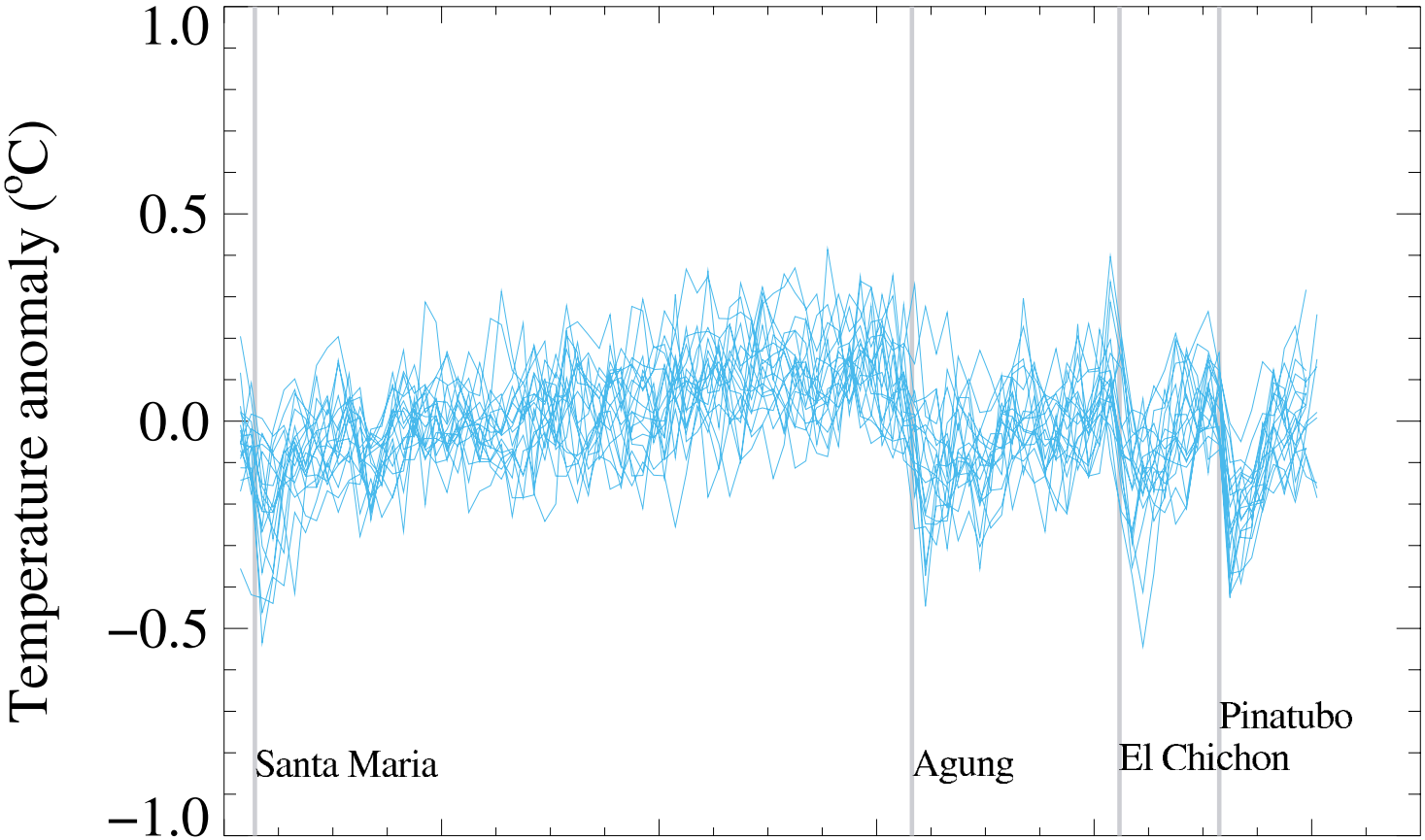

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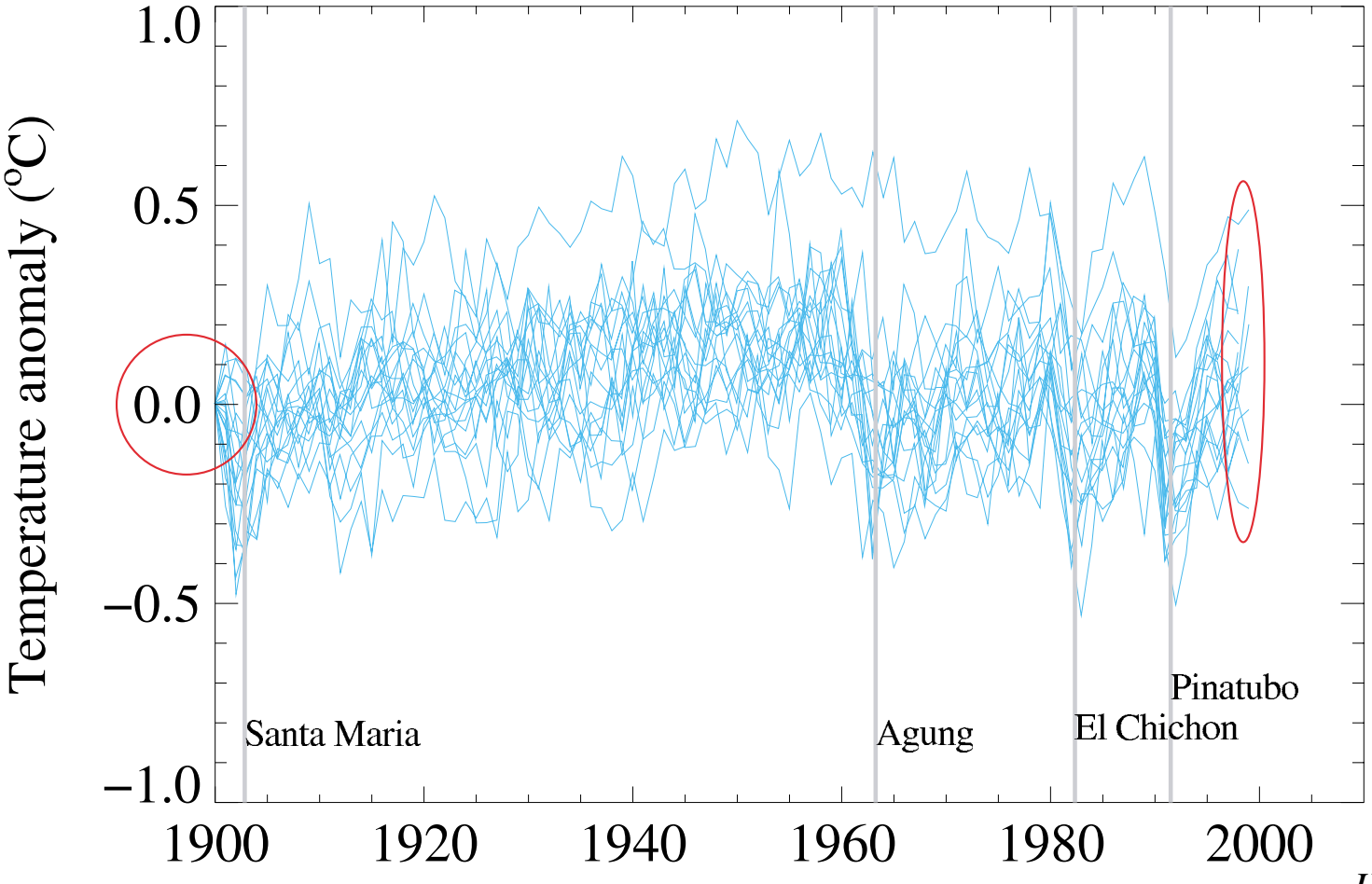
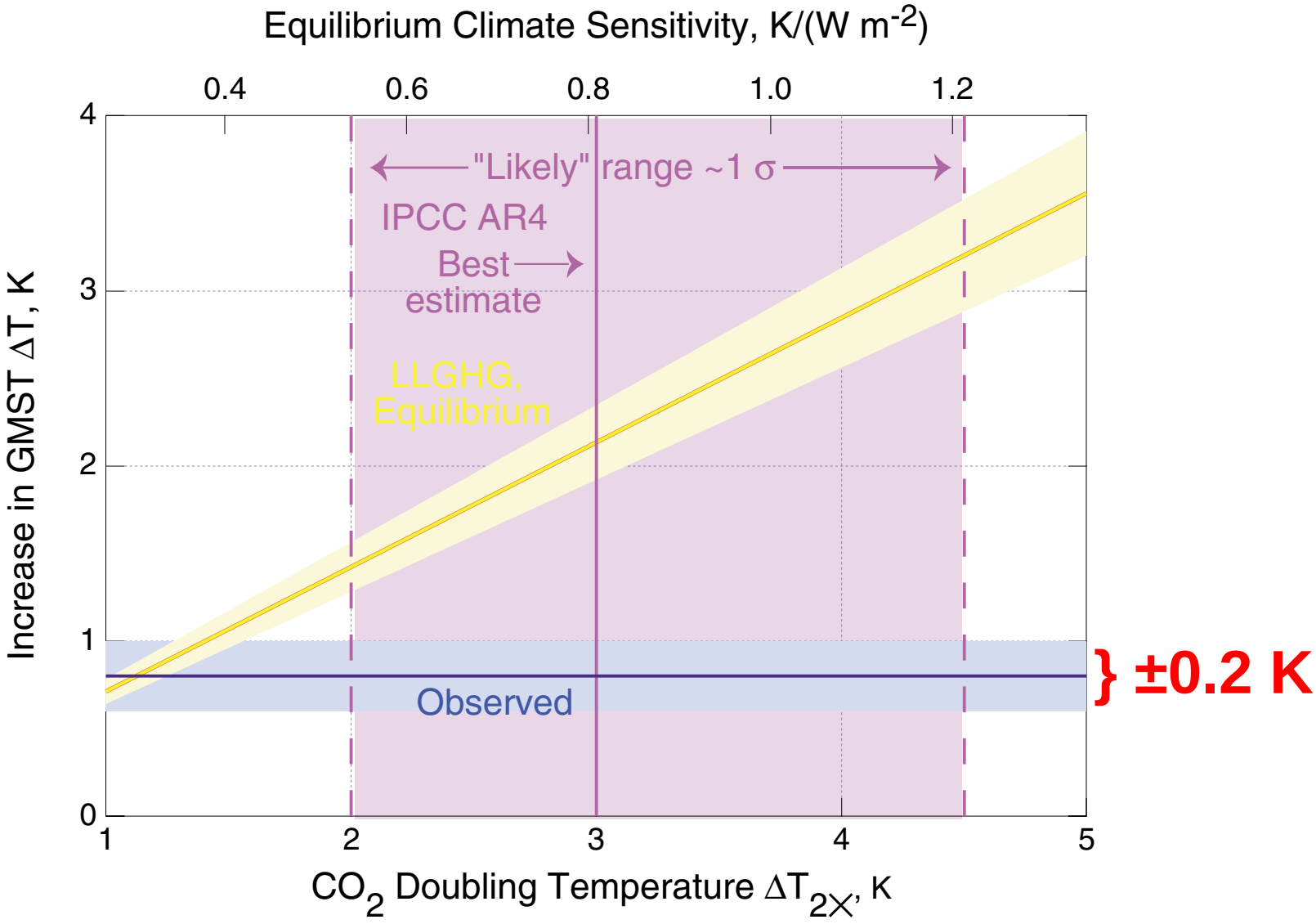


IPCC AR4

100-year difference: Average, 0.09 K; std dev, 0.19 K; maximum, 0.49 K.

EXPECTED INCREASE IN GLOBAL TEMPERATURE

Long-lived GHGs only – Dependence on climate sensitivity

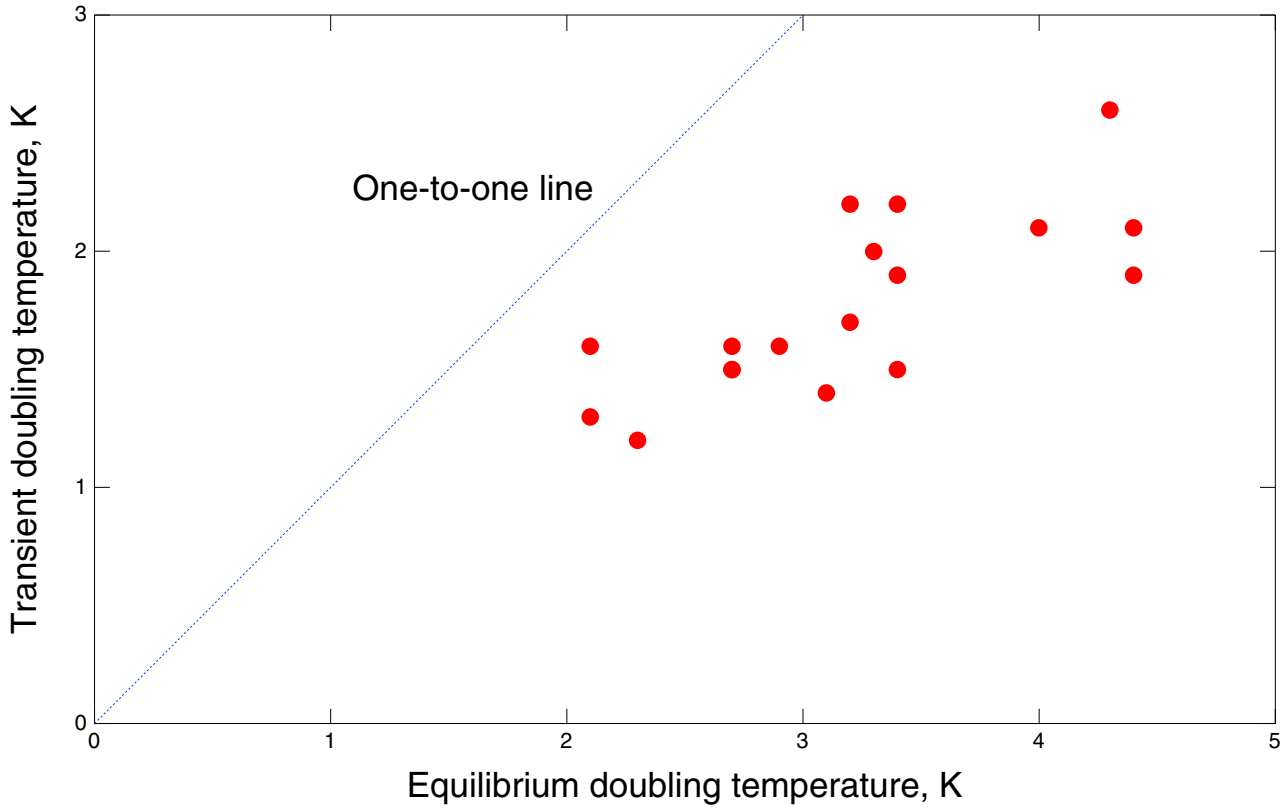


The warming discrepancy cannot be resolved by countervailing natural cooling over the industrial period.

LAG IN REACHING THERMAL EQUILIBRIUM

LAG OF TEMPERATURE RESPONSE

Increase in GMST in year 70 of 1% yr^{-1} CO_2 increase vs. equilibrium doubling temperature in 17 climate models from IPCC AR4



Data from IPCC AR4, Table 8.2

Transient sensitivity in models is only about 55% of equilibrium sensitivity.

Implies substantial unrealized "heating in the pipeline" as forcing increases.

Note: 70 years at a growth rate of 1% yr^{-1} leads to a doubling of CO_2.

ACCOUNTING FOR DISEQUILIBRIUM

Upon application of a forcing to climate initially at equilibrium

$$\text{Global heating rate} = \text{Forcing} - \text{Response}$$

Dickinson, JClim 1981
Kim, North, JGR 1992
Dutton, JClim 1995
Williams, JClim 2008
Schwartz, E&ES 2008

Solomon GRC; preprint
Tung GRC; GRL, 2008

$$H = F - S^{-1}\Delta T$$

Response is increased outgoing longwave irradiance as surface temperature T increases; S^{-1} is inverse of sensitivity.

At new equilibrium $H = 0$ and $\Delta T_{\text{eq}} = SF$.

In general $S = \Delta T / F_{\text{eff}}$ where $F_{\text{eff}} \equiv F - H$ is "effective forcing".

ACCOUNTING FOR DISEQUILIBRIUM

Approach

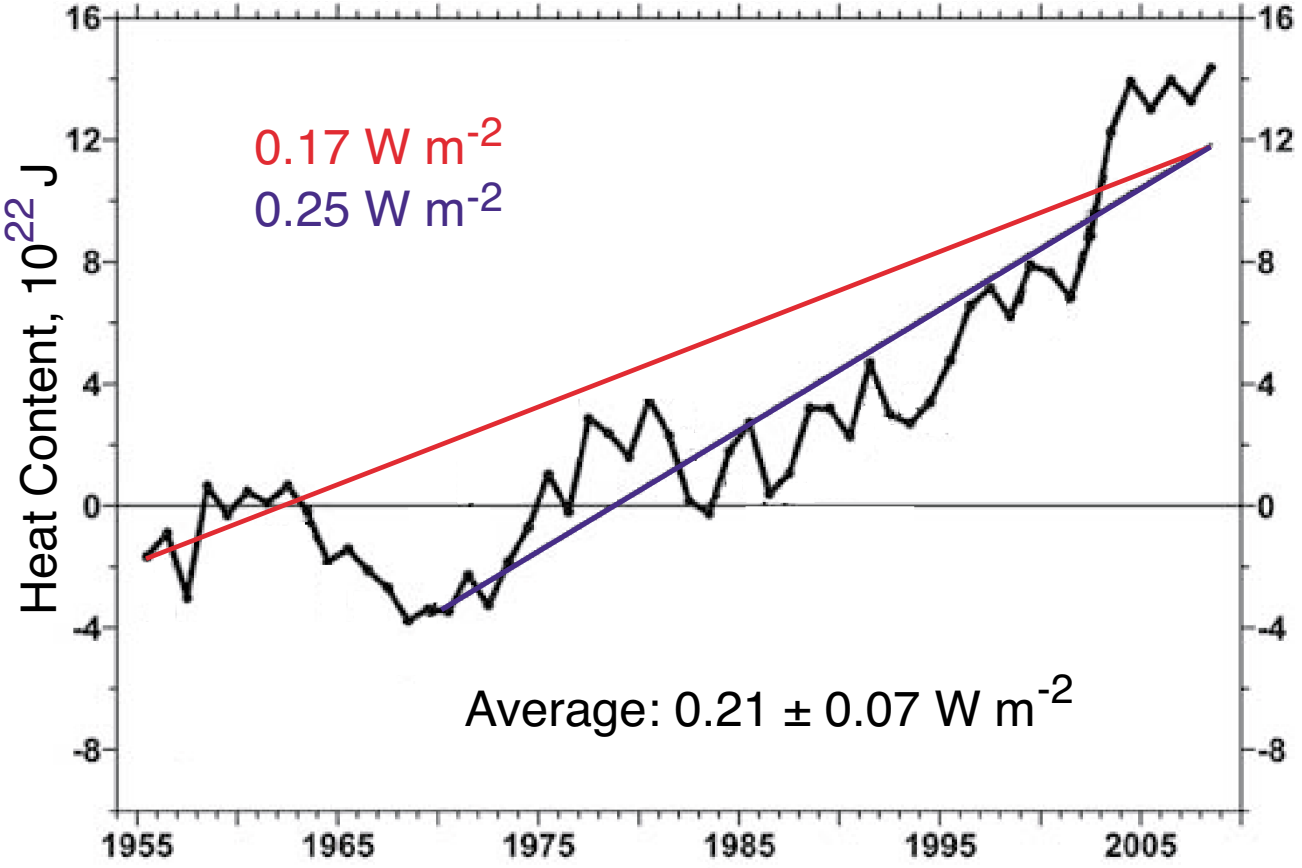
Determine global heating rate from increase in heat content of global ocean.

Evaluate *effective forcing* as $F_{\text{eff}} \equiv F - H$.

Compare observed ΔT to that expected for effective forcing.

GLOBAL HEATING RATE FROM OCEAN HEAT CONTENT

Heat content of global ocean – surface to 700 m



Hansen, Science 2005

Levitus et al., GRL, 2009

Accounting for heat to 3 km: factor of 1.44.

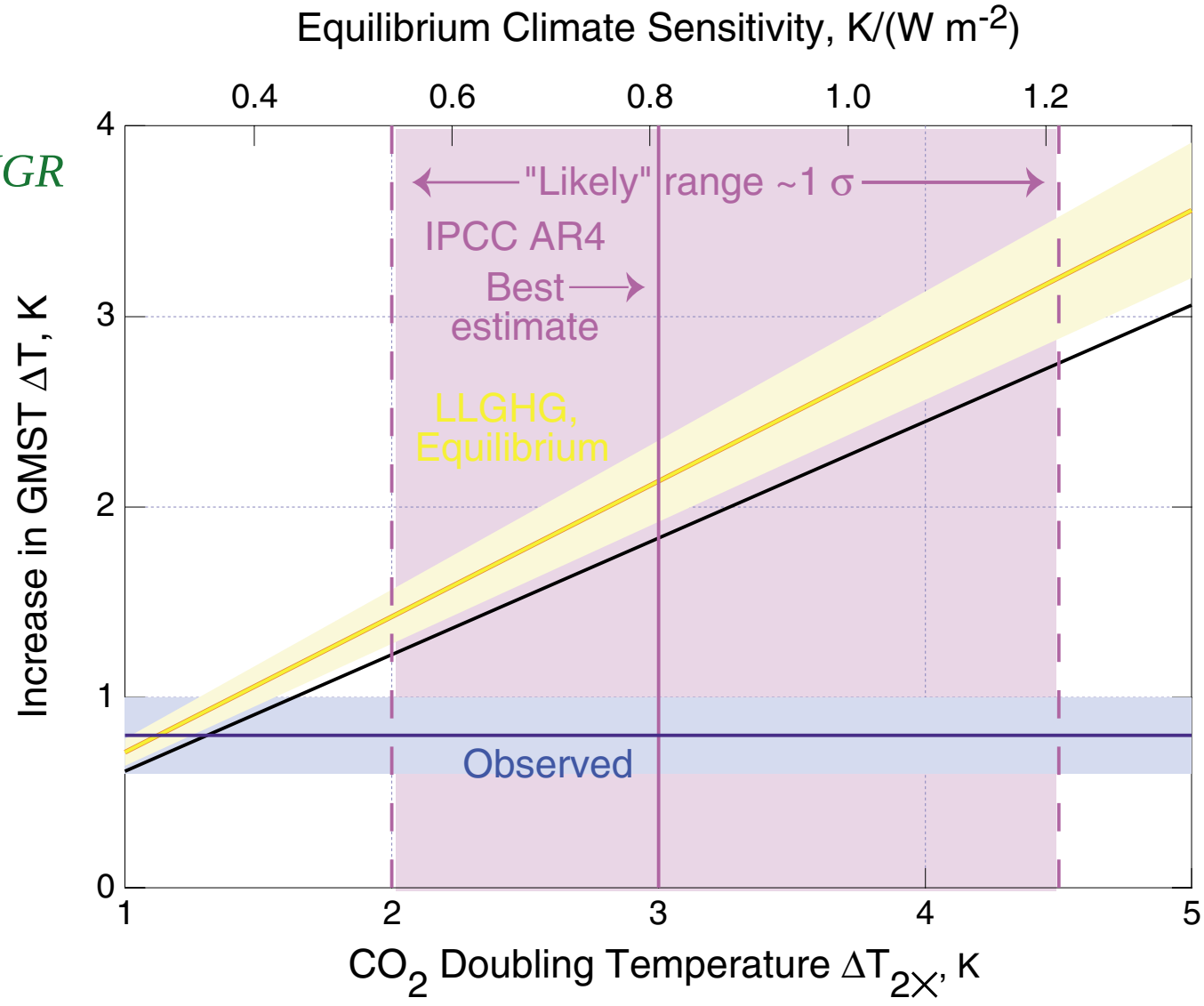
Accounting for other heat sinks (air, land, melting of ice) factor of 1.19.

Total heating rate 0.37 ± 0.12 W m^{-2}. ==> $F_{eff} = 2.63-0.37 = 2.26$ W m^{-2}

EXPECTED INCREASE IN GLOBAL TEMPERATURE

Long-lived GHGs only – Dependence on climate sensitivity

Schwartz, JGR 2007,2008



Ramanathan Feng, PNAS 2008

Hansen, Science 2005

Meehl, Science 2005

Wigley, Science 2005

Friedlingstein Solomon, PNAS 2005

Little of the warming discrepancy can attributed to thermal disequilibrium.

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

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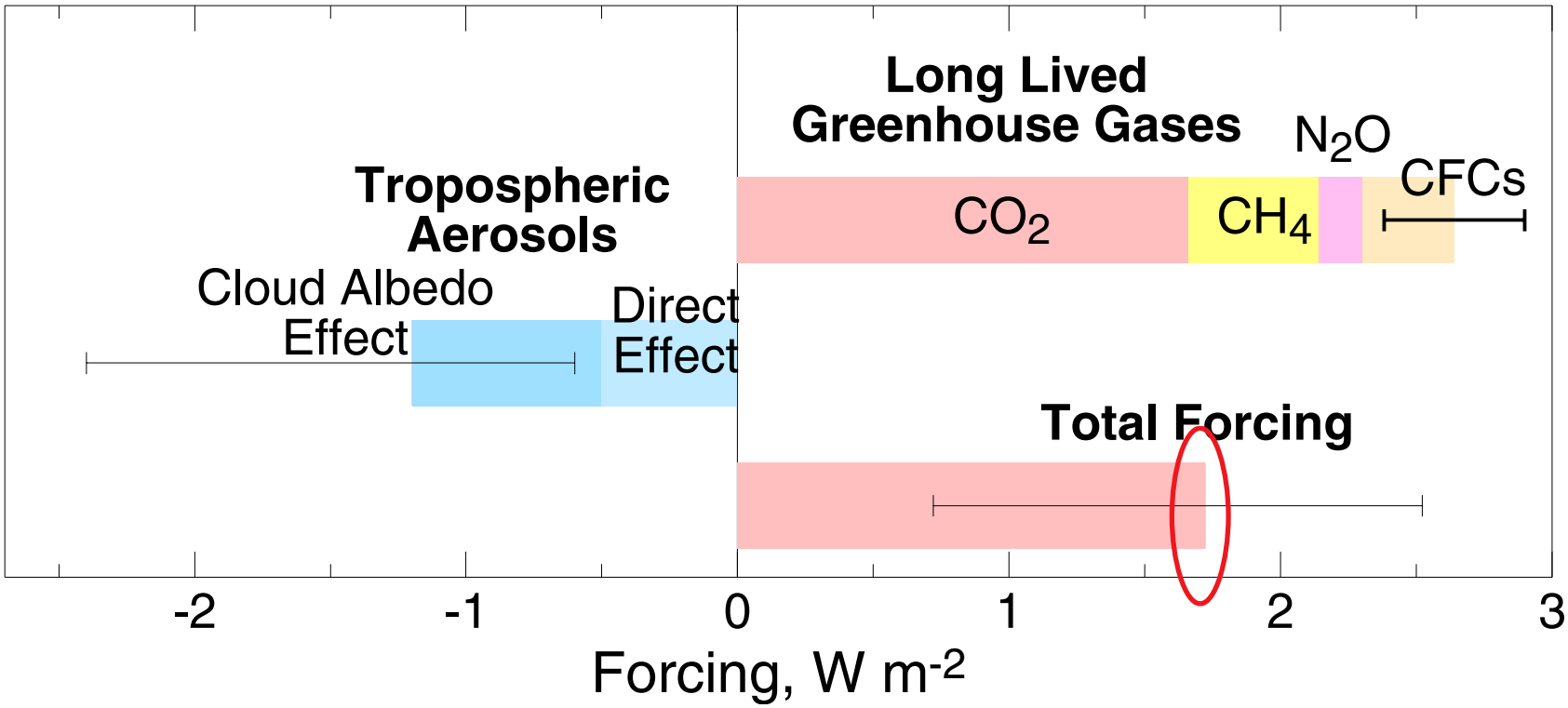


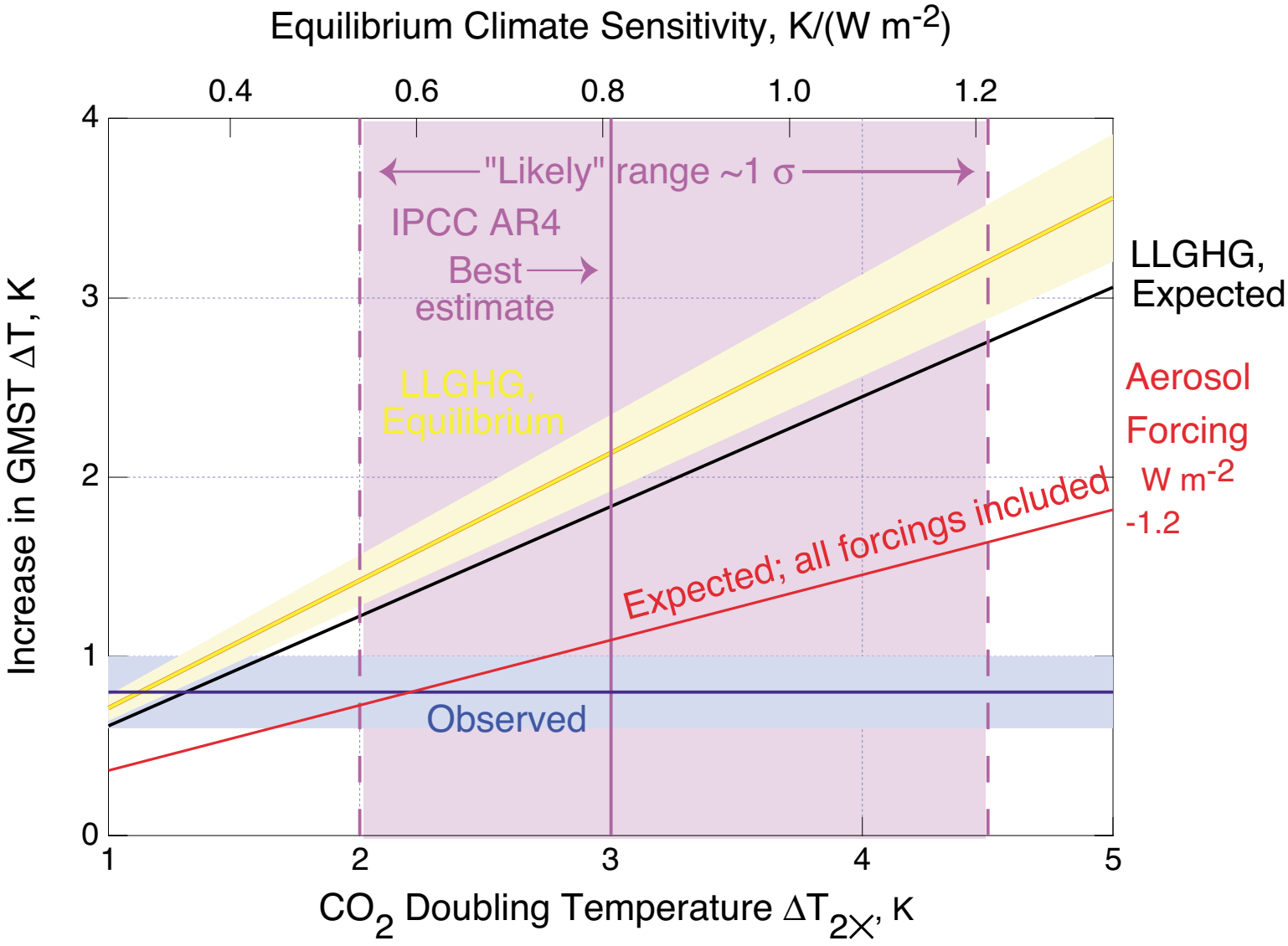
Total forcing includes other anthropogenic and natural (solar) forcings.

Forcing by tropospheric ozone, ~0.35 W m^{-2}, is the greatest of these.

Note: Likely range of ozone forcing is +0.25 to +0.65 W m^{-2}

EXPECTED INCREASE IN GLOBAL TEMPERATURE

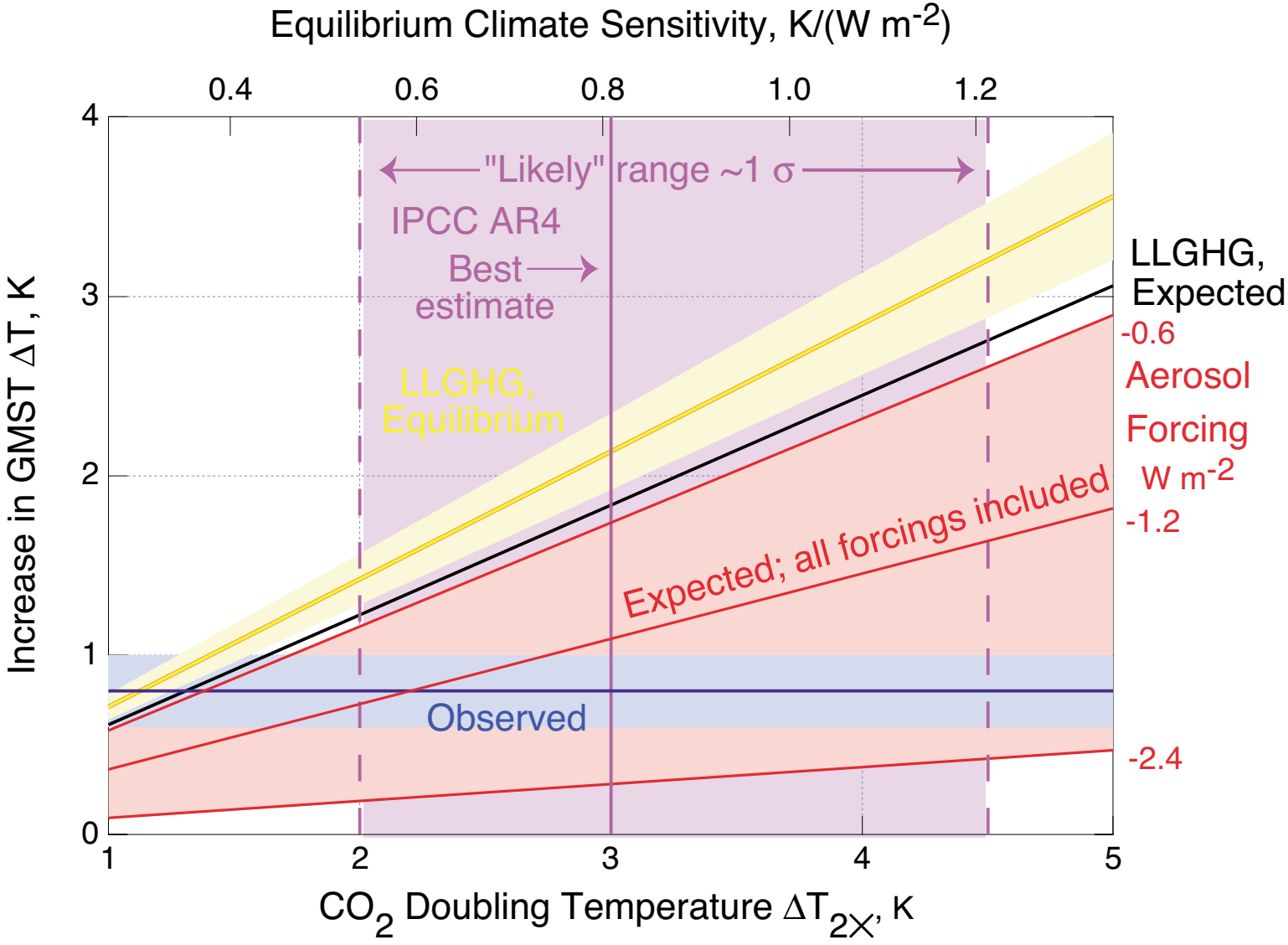
All forcings – Dependence on climate sensitivity



The warming discrepancy might be resolved by countervailing aerosol forcing (at the IPCC best-estimate value) together with low sensitivity.

EXPECTED INCREASE IN GLOBAL TEMPERATURE

All forcings – Dependence on climate sensitivity



The warming discrepancy is certainly resolved by countervailing aerosol forcing (within the IPCC range) for virtually any value of sensitivity.

WHY HASN'T EARTH WARMED AS MUCH AS EXPECTED. . .

FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

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IMPLICATIONS

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ALLOWABLE FUTURE CO_2 EMISSIONS

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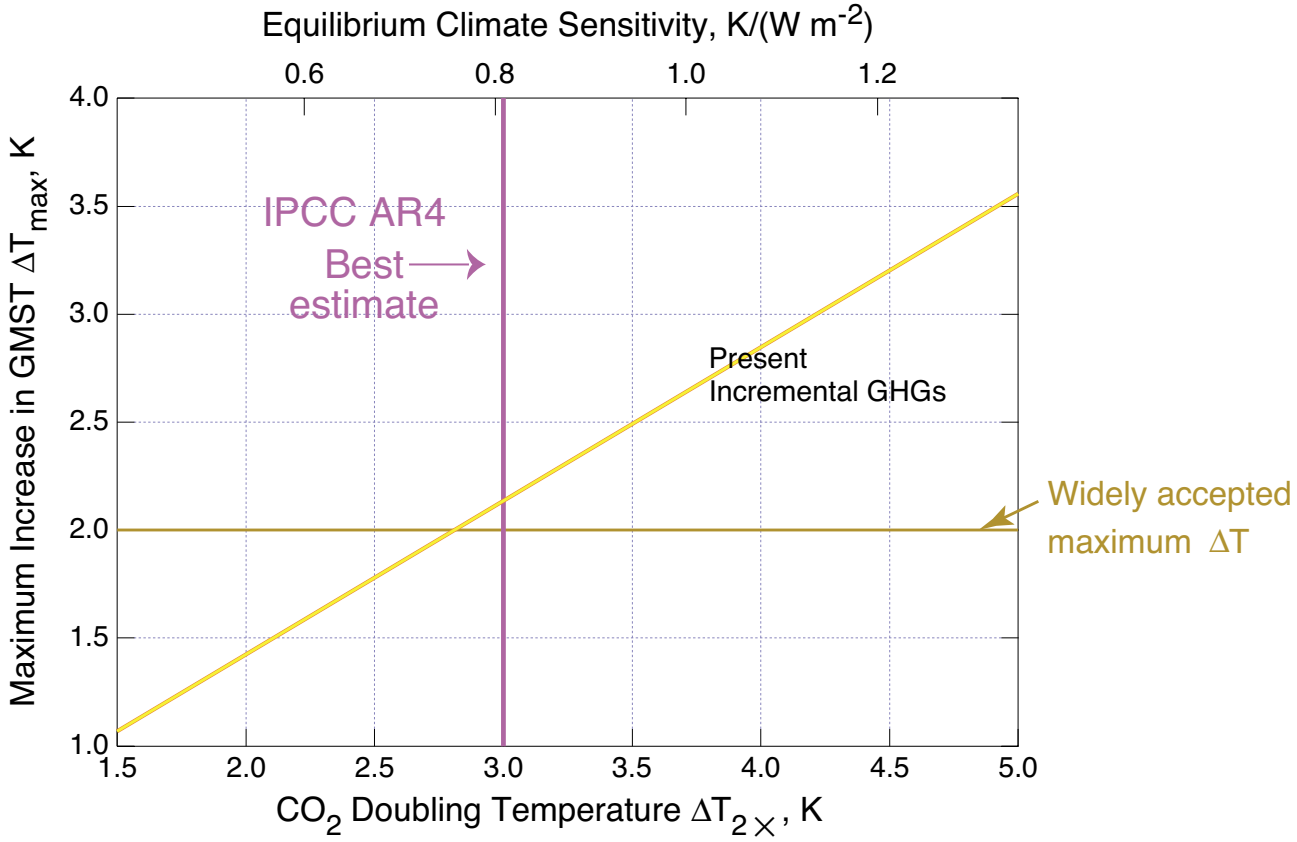
Dependence on climate sensitivity and acceptable increase in temperature relative to preindustrial

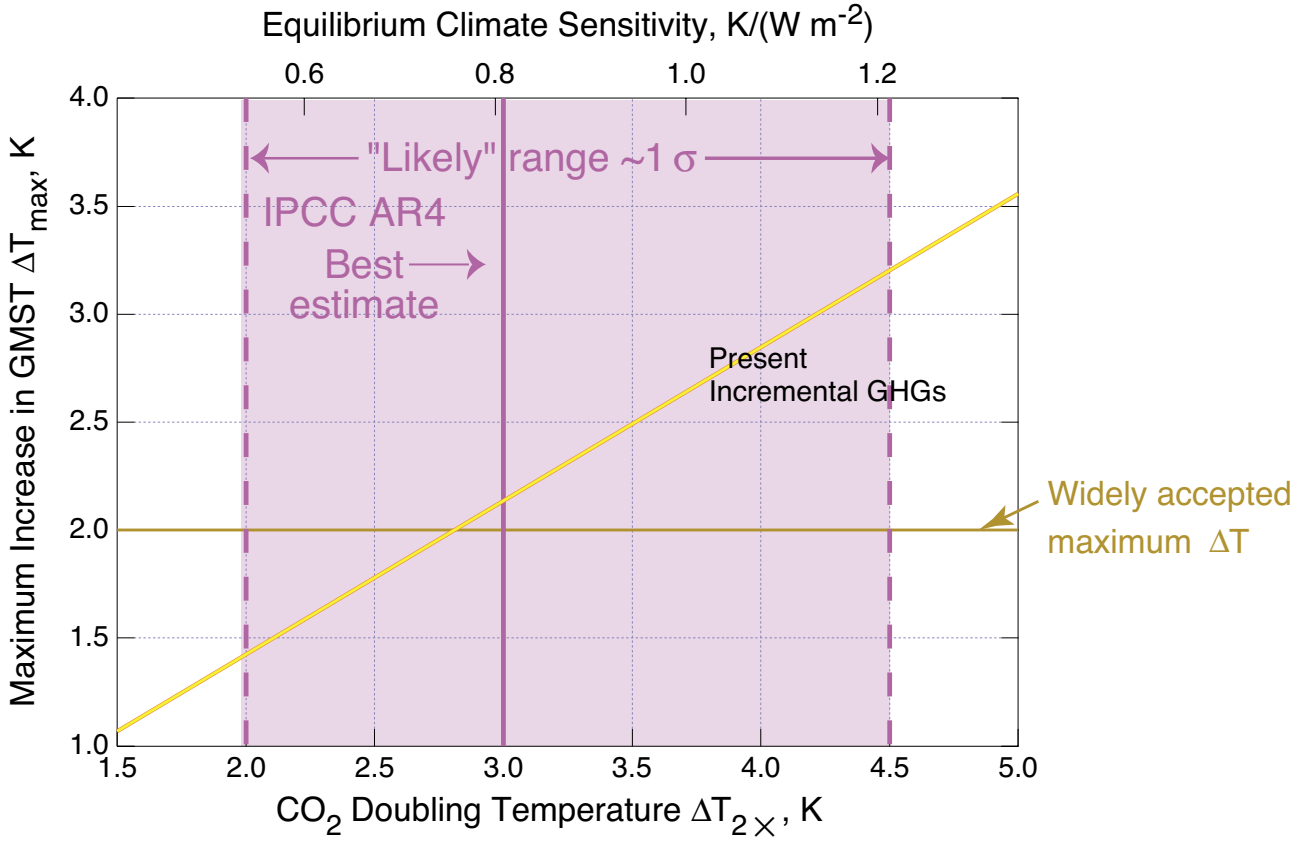


For $\Delta T_{\max} = 2$ K,

If sensitivity $\Delta T_{2x} \gtrsim 2.8$ K, ***no further emissions!***

ALLOWABLE FUTURE CO_2 EMISSIONS

Dependence on climate sensitivity and acceptable increase in temperature relative to preindustrial

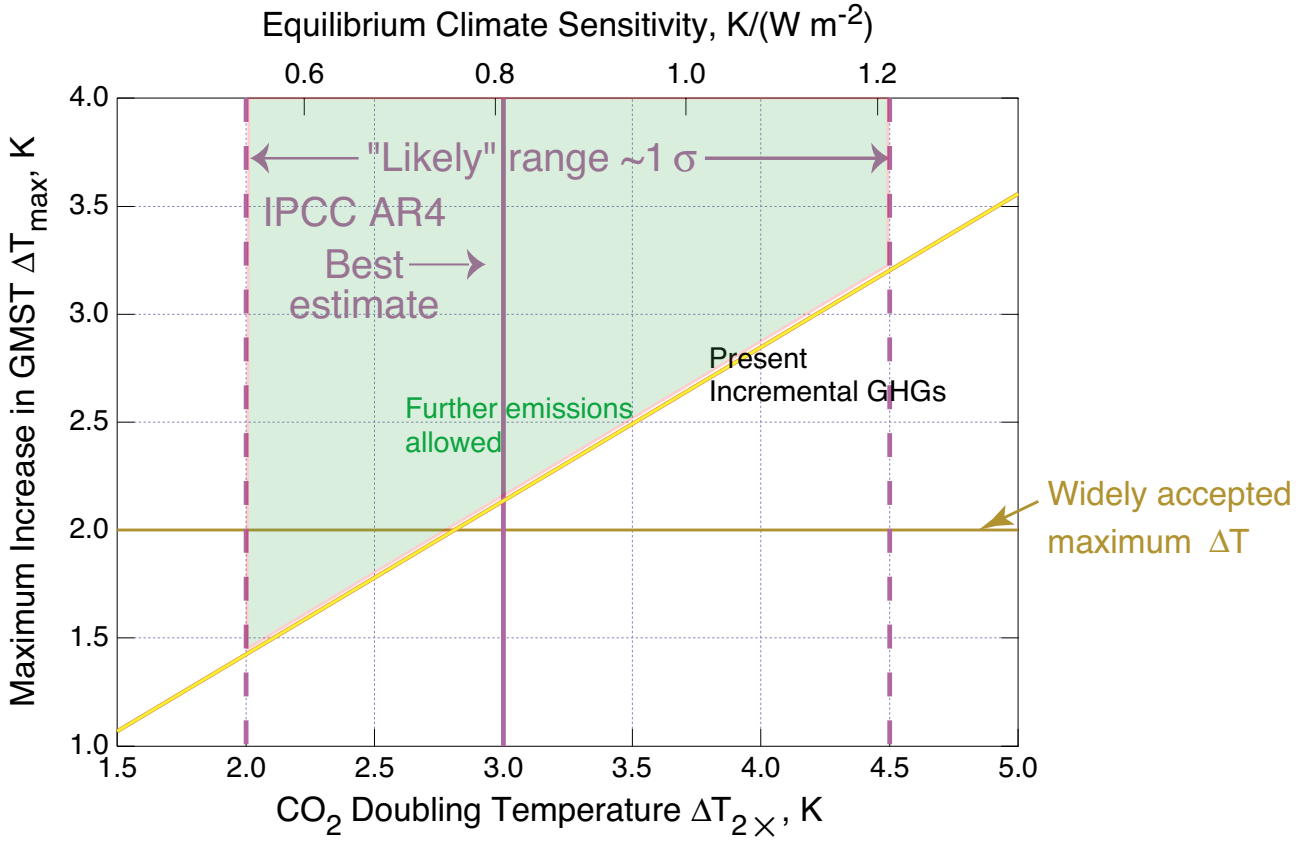


For $\Delta T_{\max} = 2$ K,

Allowability of future emissions depends on climate sensitivity.

ALLOWABLE FUTURE CO_2 EMISSIONS

Dependence on climate sensitivity and acceptable increase in temperature relative to preindustrial



If $\Delta T_{max} > 2.1$ K and/or sensitivity $\Delta T_{2x} < 2.8$ K, further emissions are allowed without exceeding ΔT_{max}.

ALLOWABLE FUTURE CO_2 EMISSIONS

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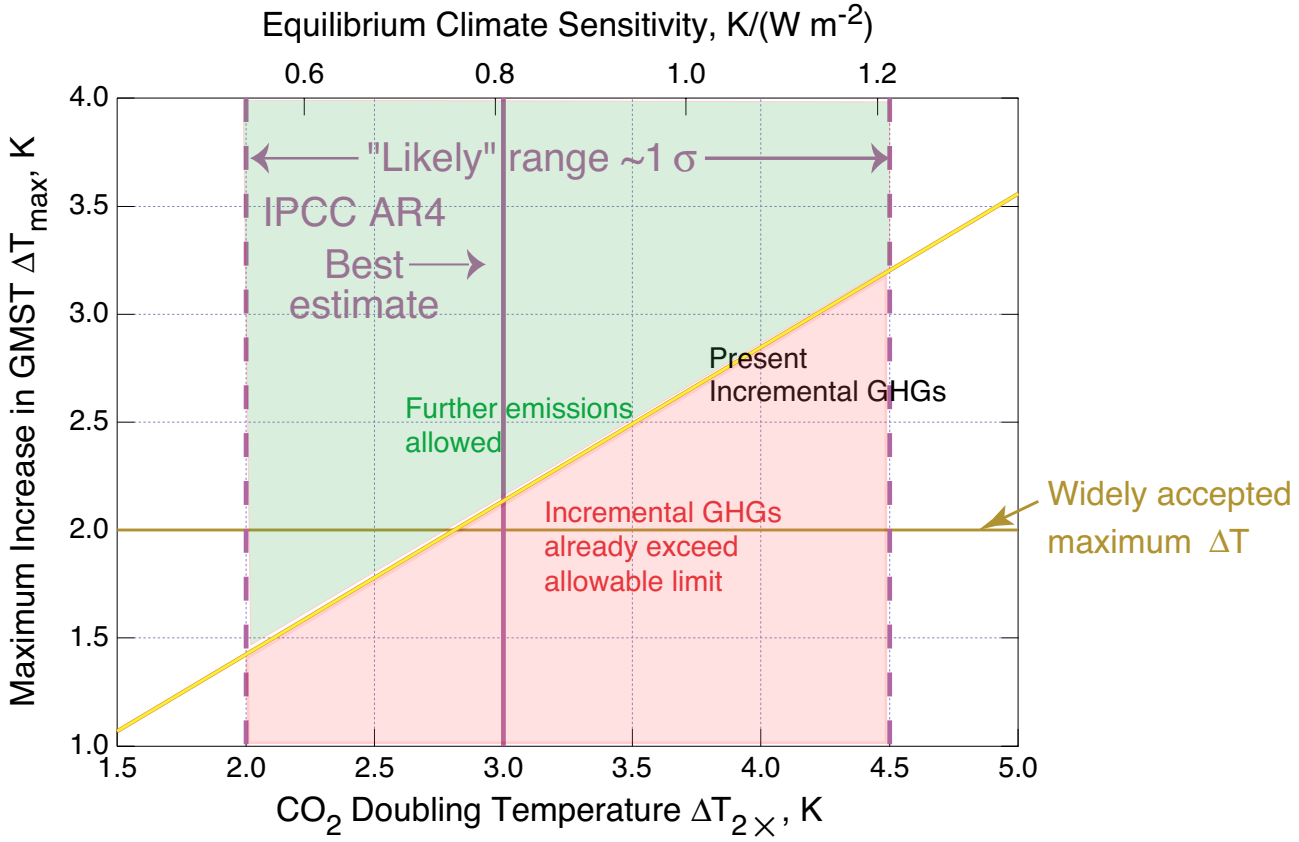


If $\Delta T_{max} > 2.1$ K and/or sensitivity $\Delta T_{2x} < 2.8$ K, further emissions are allowed without exceeding ΔT_{max}.

If $\Delta T_{max} < 2.1$ K and/or sensitivity $\Delta T_{2x} > 2.8$ K, committed temperature increase already exceeds ΔT_{max}.

IMPLICATIONS

ALLOWABLE FUTURE CO_2 EMISSIONS

How much fossil carbon can be burned and emitted into the atmosphere (as CO_2) without exceeding a given threshold for "dangerous anthropogenic interference" with the climate system?

Answer depends on target threshold and climate sensitivity.

Premise of the calculation:

Forcings by LLGHG's only; result expressed as equivalent CO_2.

MAXIMUM ALLOWABLE CO_2 MIXING RATIO

$$\text{Max } \Delta \text{ CO}_2 \text{ mixing ratio} = \left(\begin{matrix} \text{Max} \\ \Delta \text{ temp} \end{matrix} - \begin{matrix} \text{Current} \\ \text{committed} \\ \Delta \text{ temp} \end{matrix} \right) / \left(\text{Sensitivity} \times \begin{matrix} \text{Forcing} \\ \text{per } \Delta \text{ CO}_2 \end{matrix} \right)$$

$$\Delta m_{\mathrm{CO}_2} = (\Delta T_{\max} - \Delta T_{\mathrm{c}}) / Sf$$

$$\Delta m_{\mathrm{CO}_2} = \Delta T_{\max} / Sf - F_{\mathrm{c}} / f$$

$$f \approx 0.014 \text{ W m}^{-2} \text{ ppm}^{-1}$$

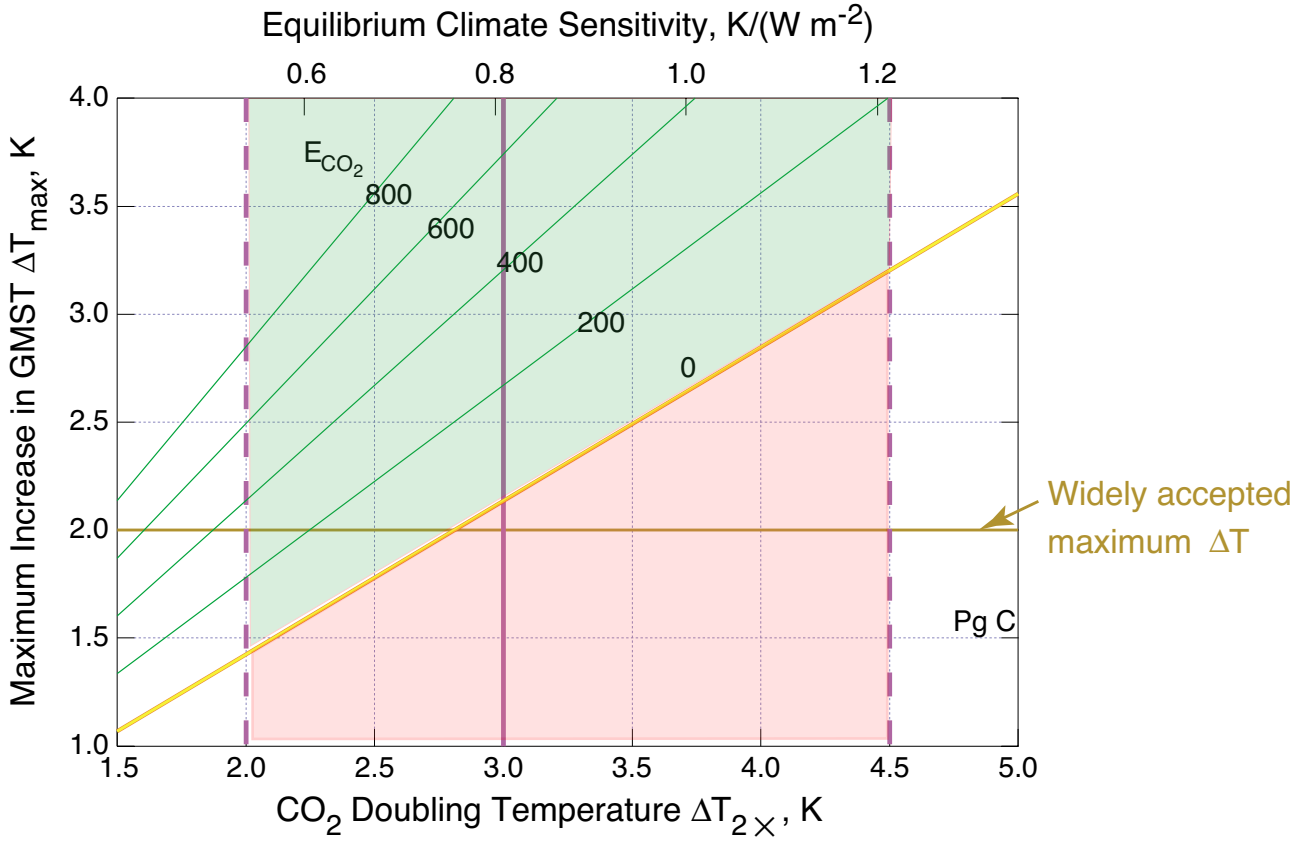
ALLOWABLE FUTURE CO_2 EMISSIONS

$$\text{Allowable } CO_2 \text{ emissions} = \text{Max } \Delta\, CO_2 \text{ mixing ratio} \Big/ \left(\begin{array}{l} \text{Conversion} \\ \text{factor, ppm} \\ \text{per PgC} \end{array} \times \begin{array}{l} \text{Airborne fraction} \\ \text{of emitted } CO_2, \\ \sim 0.5 \end{array} \right)$$

$$E_{CO_2} = \Delta m_{CO_2} / cr$$

ALLOWABLE FUTURE CO_2 EMISSIONS

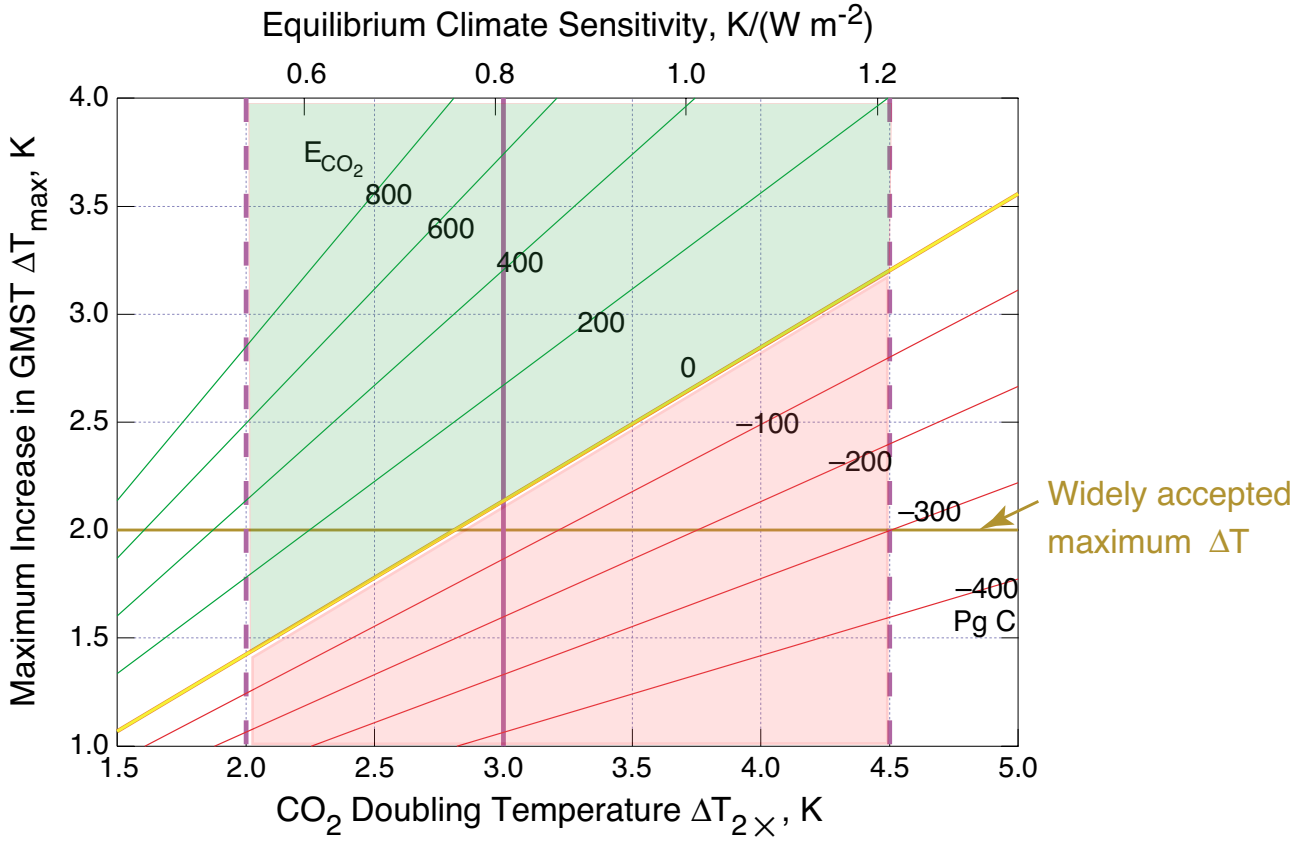
Dependence on climate sensitivity and acceptable increase in temperature relative to preindustrial



Allowable future emissions depend on climate sensitivity and $\Delta T_{\max}$.

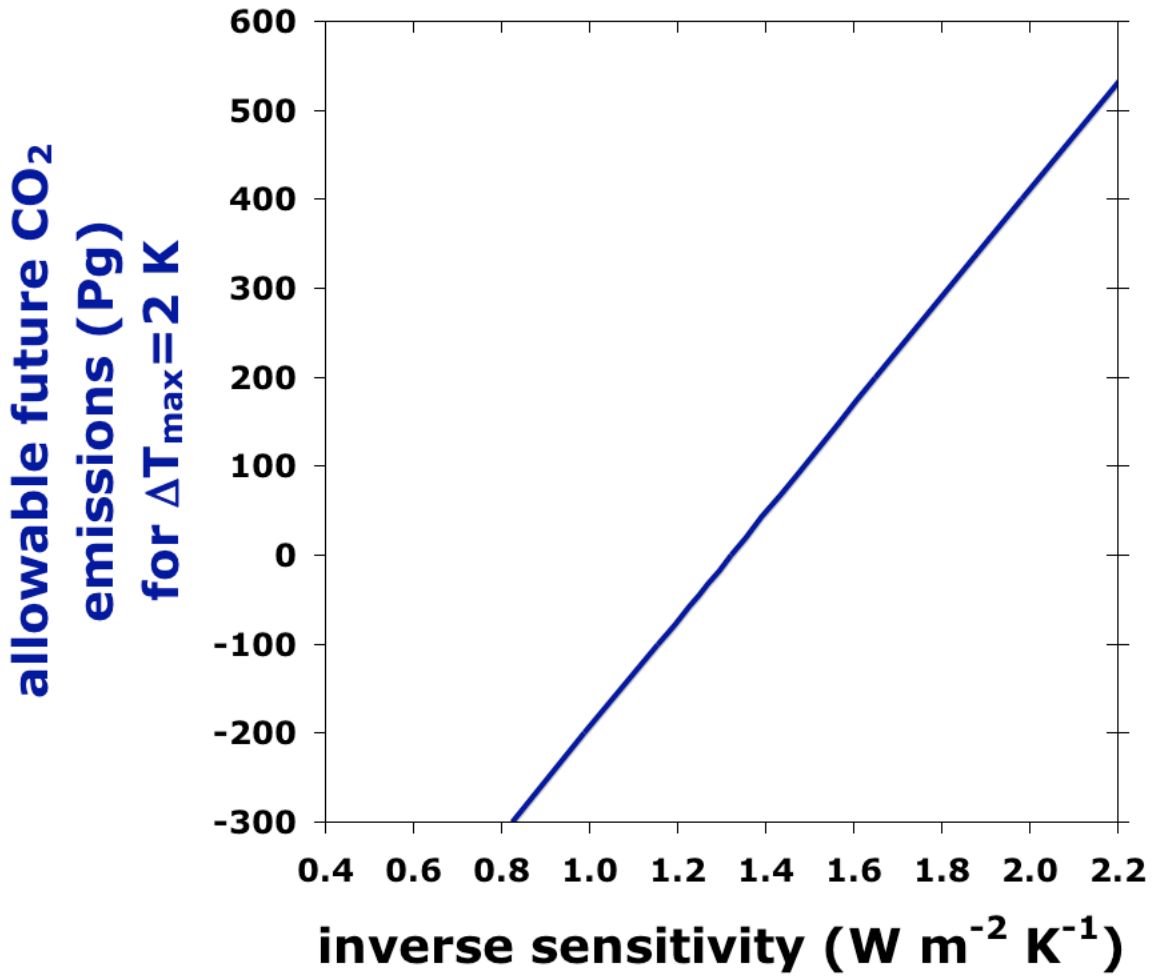
ALLOWABLE FUTURE CO_2 EMISSIONS

Dependence on climate sensitivity and acceptable increase in temperature relative to preindustrial



Allowable future emissions ***or amount by which present GHGs exceed the allowable threshold*** depend on climate sensitivity and $\Delta T_{\max}$.

ALLOWABLE FUTURE CO_2 EMISSIONS AND CLIMATE SENSITIVITY



Larger future CO_2 emissions are consonant with ΔT_{max}=2 K if climate sensitivity is low (inverse sensitivity is high).

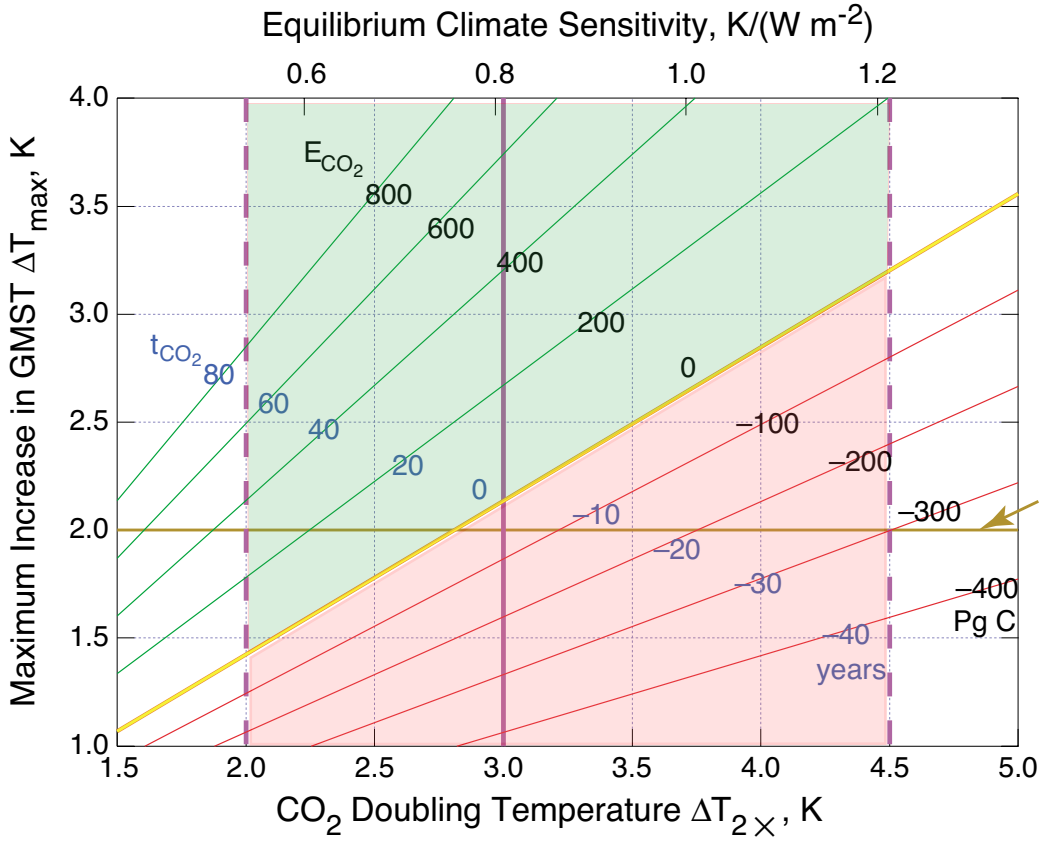
HOW LONG CAN WE CONTINUE TO EMIT CO_2 AT THE PRESENT RATE?

Years at present emission rate	=	Allowable CO_2 emissions	/	Present CO_2 emission rate, 9 Pg yr^{-1}

$$t_{CO_2} = E_{CO_2} / q$$

ALLOWABLE FUTURE CO_2 EMISSIONS

Dependence on climate sensitivity and acceptable increase in temperature relative to preindustrial



Caldeira, Science, 2003
Edmonds in Schellnhuber, 2006
Allen, Nature, 2009

For $\Delta T_{max} = 2$ K . . .

If sensitivity ΔT_{2x} is 2 K, ~ ***30 more years of emissions at present rate***.

If sensitivity ΔT_{2x} is 2.8 K, ***no more emissions***.

If sensitivity ΔT_{2x} is 3 K, ***threshold is exceeded by ~5 years***.

If sensitivity ΔT_{2x} is 4.5 K, ***threshold is exceeded by ~30 years***.

APPROACHES TO DETERMINING CLIMATE SENSITIVITY

APPROACHES TO DETERMINING CLIMATE SENSITIVITY

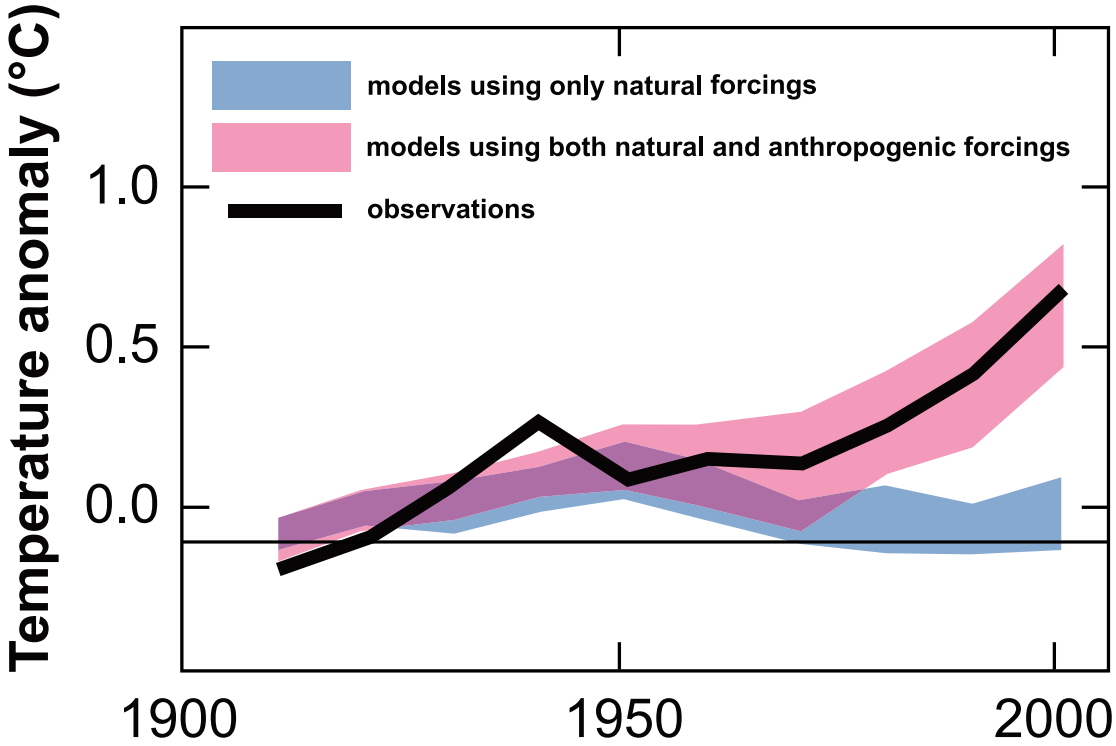
Climate models

Empirical

- Paleo: Concerns over accuracy — *Tung, GRC* *Hansen* *Ganopolski, GRL 2008*
- Sensitivity = Time constant/Heat Capacity — *Schwartz JGR 2007, 2008*
- Instrumental record

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



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IPCC AR4, 2007

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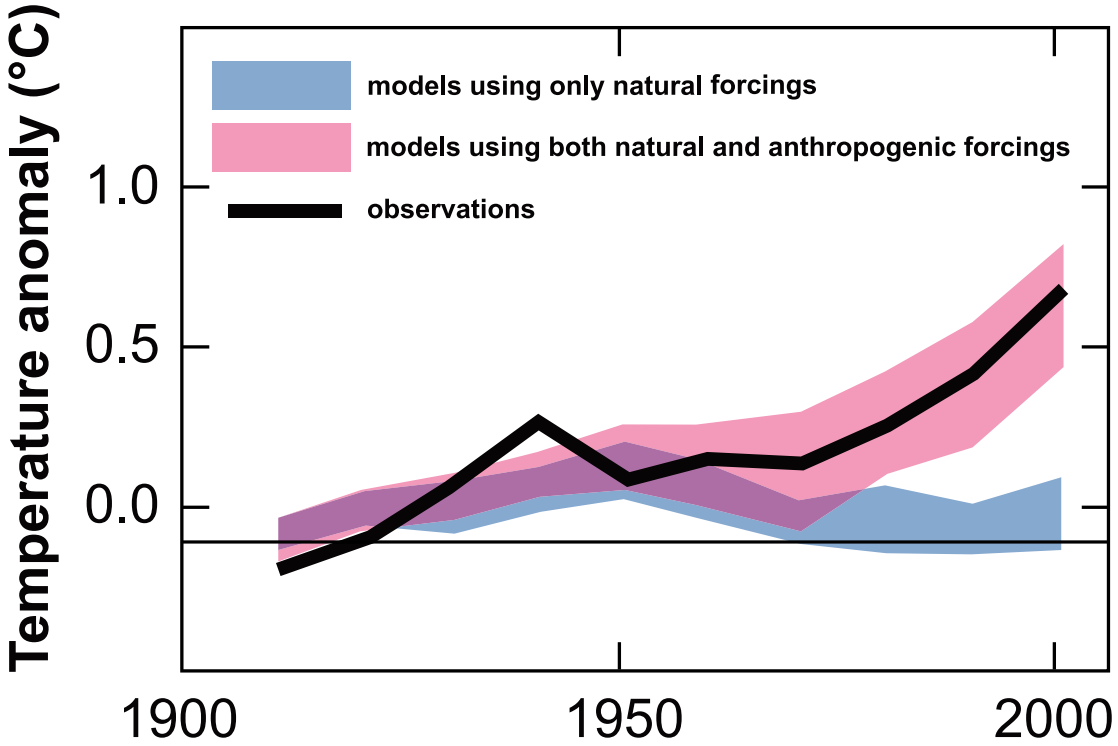

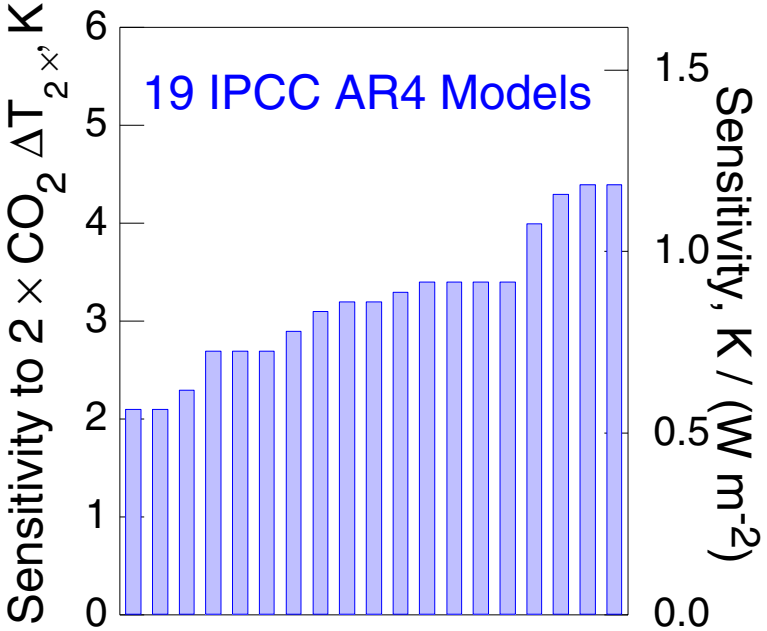

- Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a ***consistent explanation of the observed temperature record***.
- These simulations used models with ***different climate sensitivities, rates of ocean heat uptake and magnitudes and types of forcings***.

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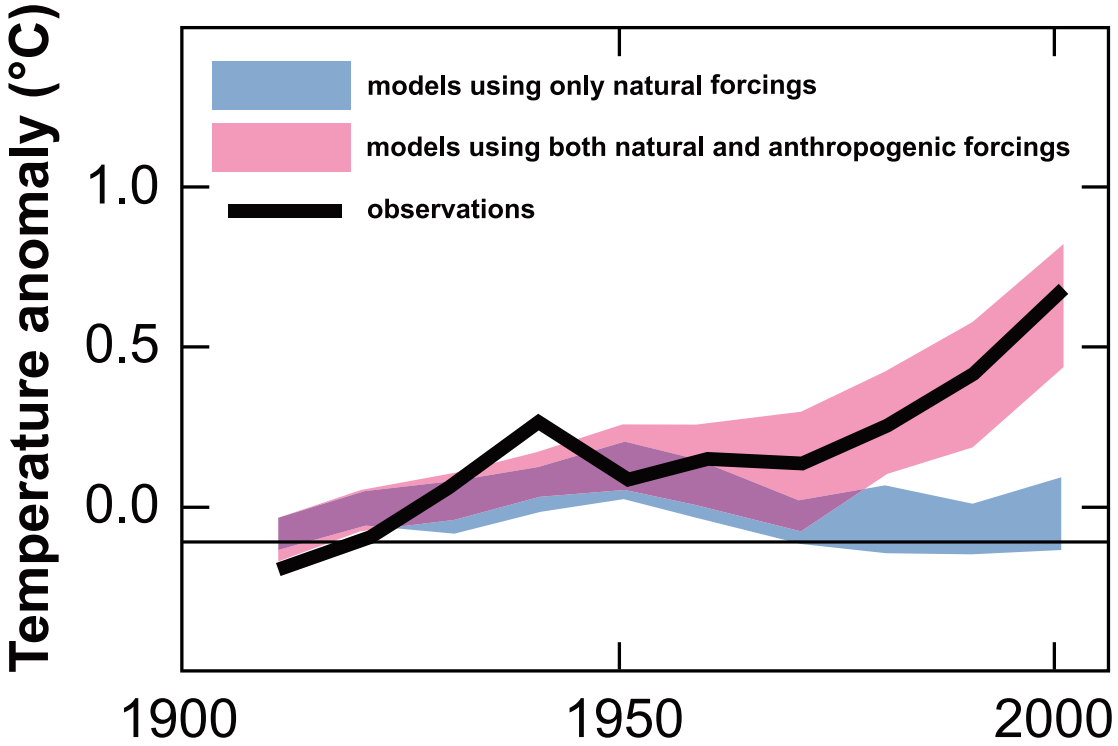

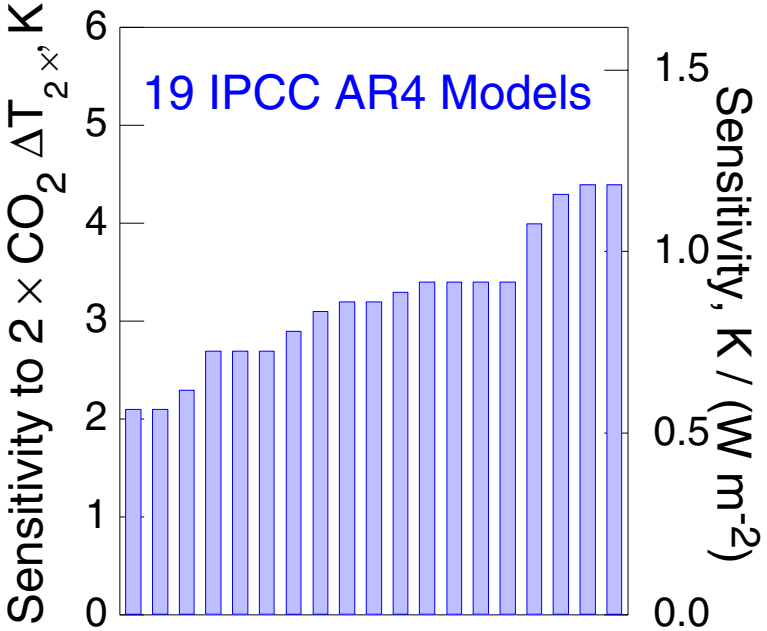

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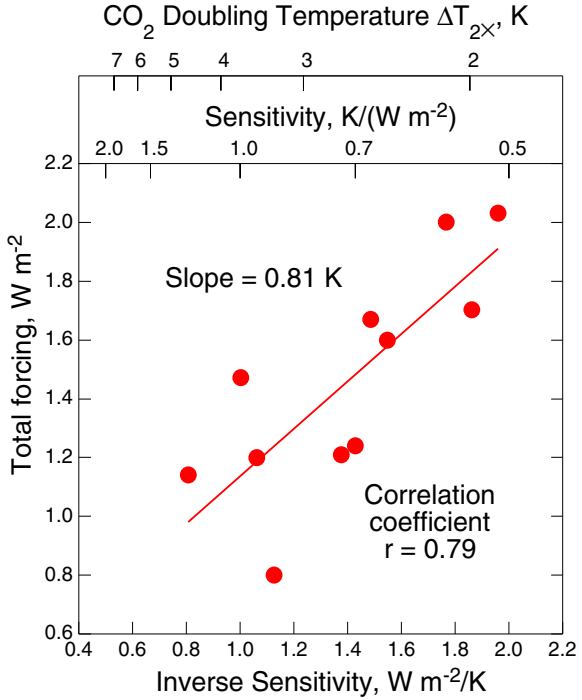
How can this be?

CORRELATION OF AEROSOL FORCING, TOTAL FORCING, AND SENSITIVITY IN CLIMATE MODELS

Nine coupled ocean-atmosphere models; two energy balance models

$$S = \Delta T / F$$

$$F = \Delta T \, S^{-1}$$



Modified from Kiehl, GRL, 2007

Total forcing is linearly correlated with inverse sensitivities of the models.

Climate models with lower sensitivity (higher inverse sensitivity) employed a greater total forcing.

Slope (0.8 K) is approximately equal to observed temperature change. Models accurately reproduce known temperature change.

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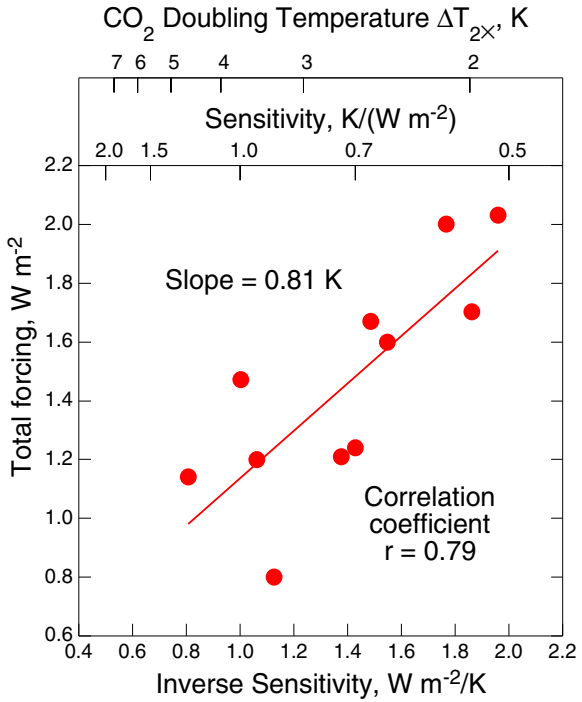

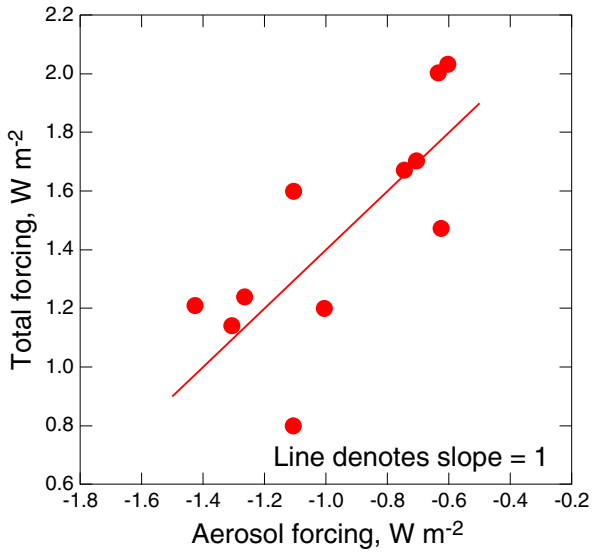

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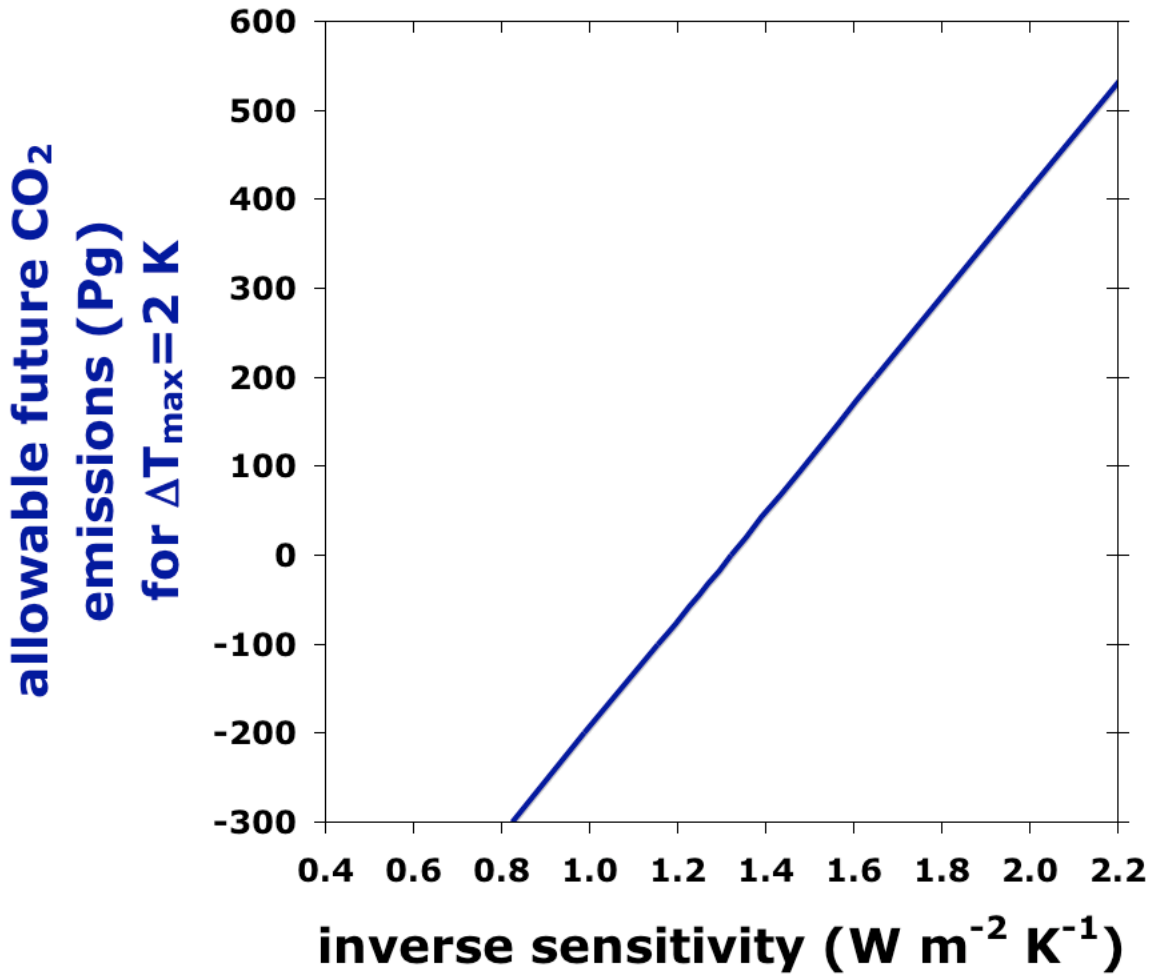
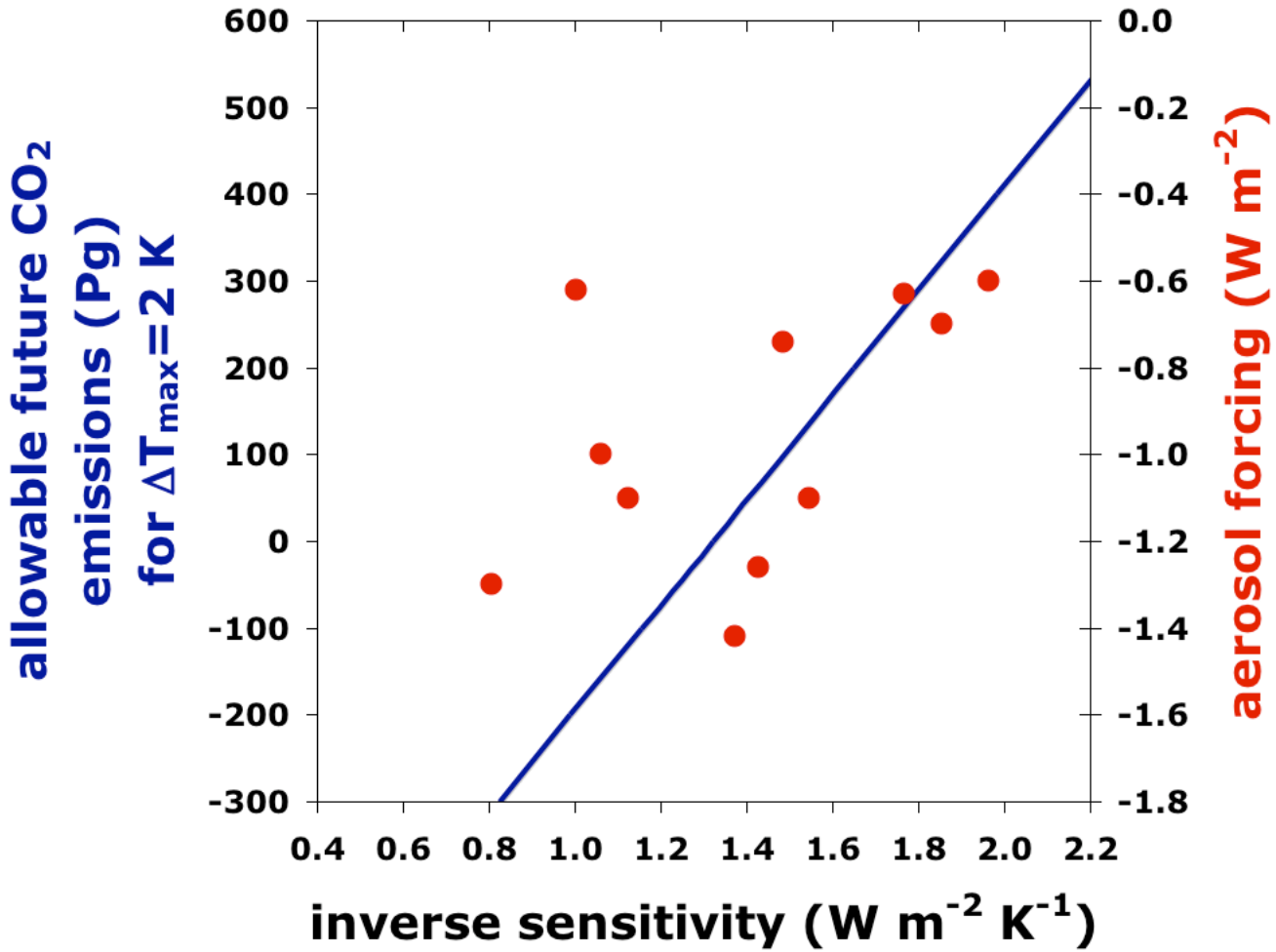
Greater total forcing is due to smaller (less negative) aerosol forcing.

ALLOWABLE FUTURE CO_2 EMISSIONS AND CLIMATE SENSITIVITY



Larger future CO_2 emissions are consonant with ΔT_{max}=2 K if climate sensitivity is low (inverse sensitivity is high).

ALLOWABLE FUTURE CO_2 EMISSIONS AND AEROSOL FORCING



A low climate sensitivity allows larger future CO_2 emissions, and is associated with models that have the lowest magnitude of aerosol forcing.

EMPIRICAL DETERMINATION OF CLIMATE SENSITIVITY

From known forcing, temperature change, and heating rate

$$\text{Temp change} = \text{Sensitivity} \times \left(\text{Forcing} - \text{Heating rate} \right) = \text{Sensitivity} \times \text{Effective forcing}$$

$$\Delta T = S(F - H) = SF_{\text{eff}}$$

or

$$F_{\text{eff}} = \Delta T S^{-1}$$

.

EMPIRICAL DETERMINATION OF CLIMATE SENSITIVITY

From known temperature change, forcing, and heating rate

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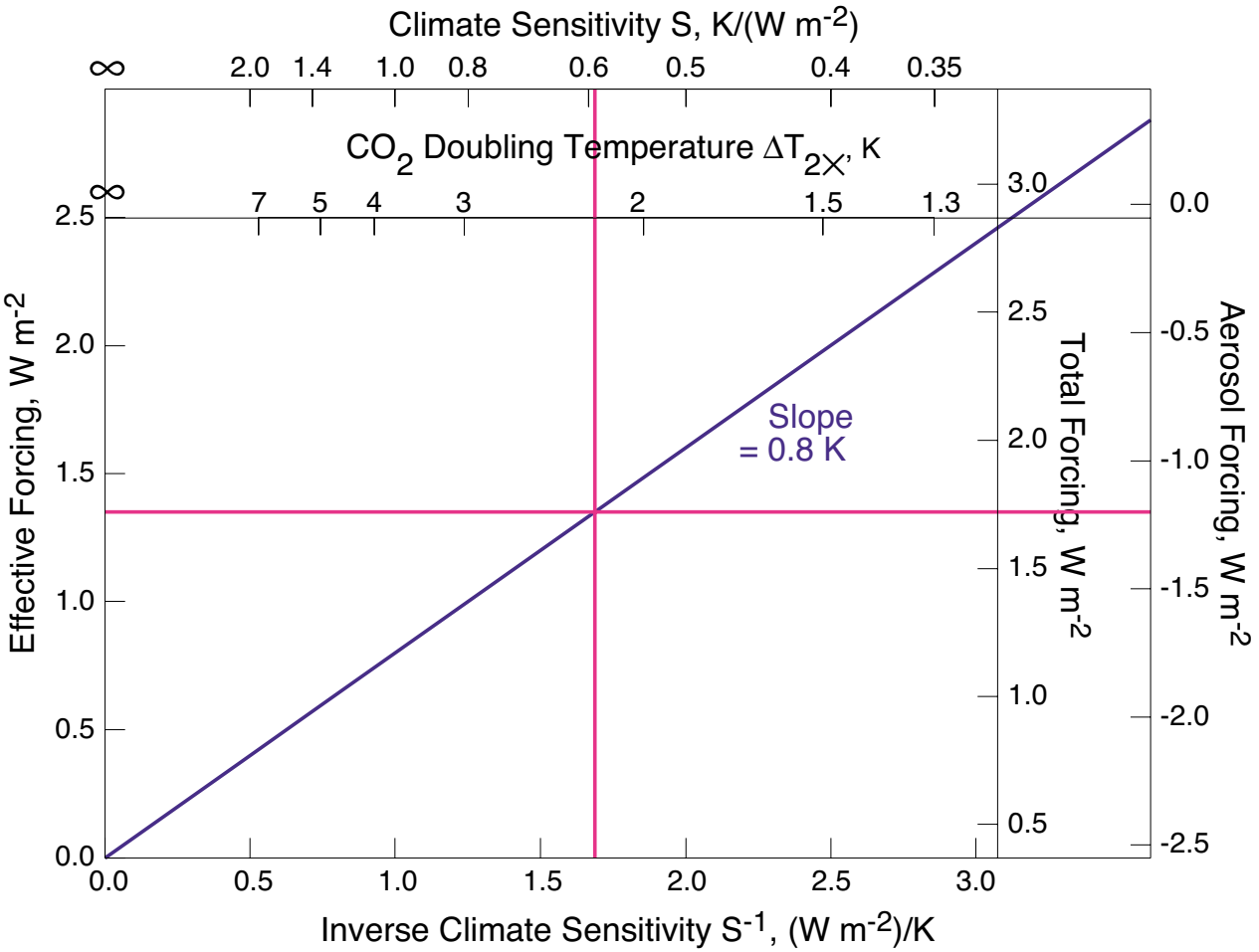


Known effective forcing intersecting with known temperature increase permits empirical determination of inverse sensitivity.

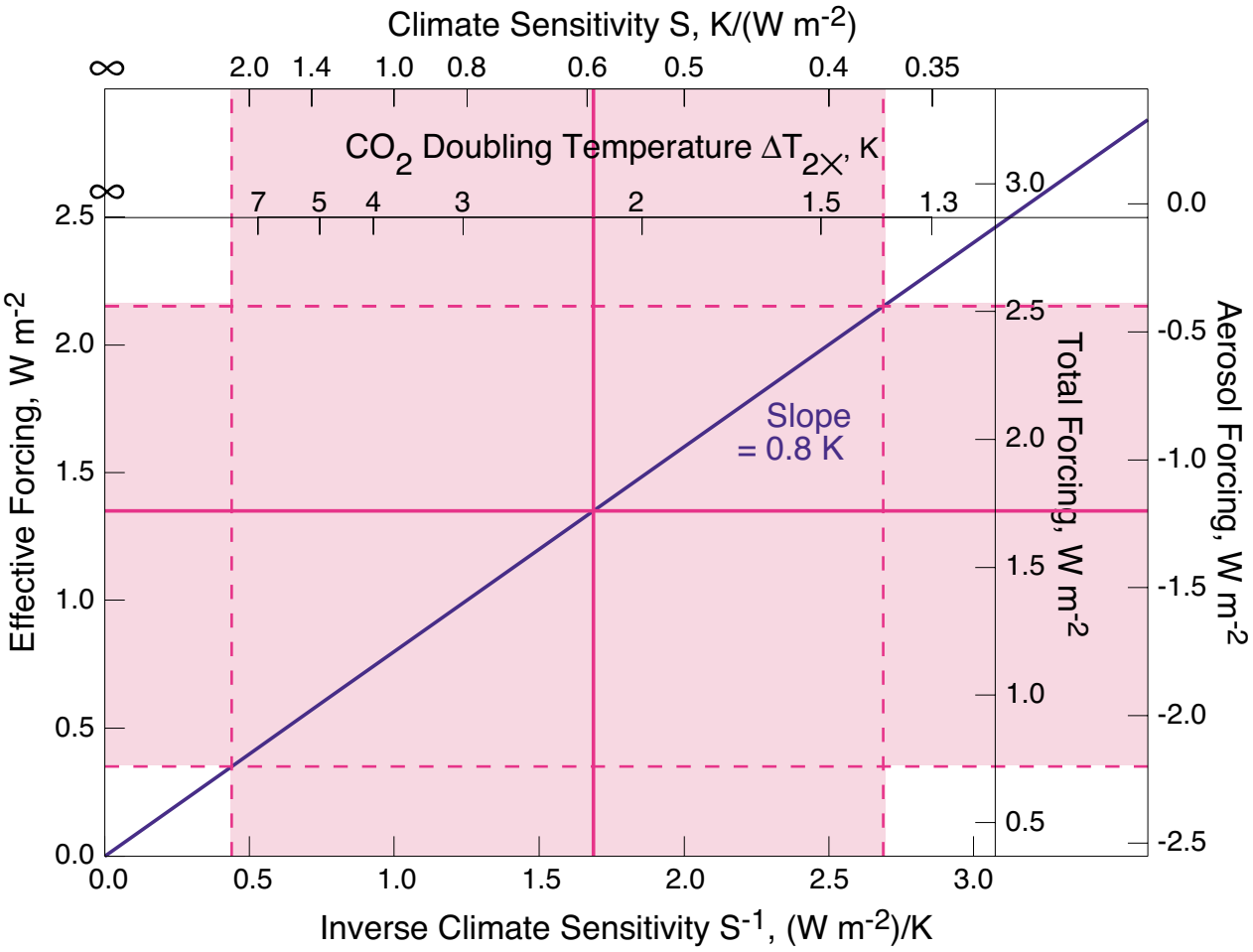
EMPIRICAL DETERMINATION OF CLIMATE SENSITIVITY

Effect of uncertainty in forcing

$$F_{\text{eff}} = F - H$$

$$\Delta T = SF_{\text{eff}}$$

$$F_{\text{eff}} = \Delta T S^{-1}$$



Present uncertainty in aerosol forcing precludes precise determination of climate sensitivity from temperature increase over industrial period.

THE BOTTOM LINE

Uncertainties in climate sensitivity and aerosol forcing are ***intrinsically coupled***, in climate models and in empirical determination of sensitivity.

As a result of these uncertainties, the amount of incremental CO_2 (and other greenhouse gases) that can be added to the present atmosphere consonant with a given maximum increase in global mean surface temperature above preindustrial is ***unknown even in sign***.

THE PATH FORWARD

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Determine aerosol forcing with high accuracy.

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Multiple approaches are required:

Laboratory studies of aerosol processes.

Field measurements of aerosol processes and properties: emissions, new particle formation, evolution, size distributed composition, optical properties, CCN properties, removal processes . . .

Represent aerosol processes in ***chemical transport models***.

Evaluate models by ***comparison with observations***.

Satellite measurements for spatial coverage.

Calculate forcings in ***chemical transport models and GCMs***.

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Measurement based determination of aerosol forcings.

CONCLUSIONS

The increase in global mean surface temperature over the industrial period is ***less than 40%*** of what would be expected from forcing by incremental long-lived greenhouse gases for the IPCC best estimate of equilibrium climate sensitivity (CO_2 doubling temperature 3 K).

This "warming discrepancy" cannot be resolved by ***uncertainty in GHG forcing***, ***lag in reaching thermal equilibrium*** or ***countervailing natural cooling*** of the climate system.

The warming discrepancy is due to ***aerosol forcing*** and/or ***climate sensitivity*** less than IPCC best estimate.

CONCLUSIONS (*cont'd*)

The amount of incremental CO_2 (and other greenhouse gases) that can be added to the present atmosphere consonant with a given maximum increase in global mean surface temperature above preindustrial is ***unknown even in sign***.

This uncertainty is a consequence of present ***uncertainty in climate sensitivity***.

Uncertainty in climate sensitivity is intrinsically linked to uncertainty in climate forcing, mainly due to ***uncertainty in forcing by tropospheric aerosols***.

Confident determination of climate sensitivity requires ***greatly reducing uncertainty in forcing by aerosols***.