WHY HASN'T EARTH WARMED AS MUCH AS EXPECTED?

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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.

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}.

THE WARMING DISCREPANCY

For increases in CO_2, CH_4, N_2O, and CFCs over the industrial period

$$F = 2.6 \text{ W m}^{-2}$$

Expected temperature increase

$$\Delta T_{\text{exp}} = \frac{F}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.6}{3.7} \times 3 \text{ K} = 2.1 \text{ K}$$

Observed temperature increase

$$\Delta T_{\text{obs}} = 0.8 \text{ K}$$

How can we account for this ***warming discrepancy***?

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

Global energy balance: $$\frac{dH}{dt} = Q - E = \frac{\gamma J_S}{4} - \varepsilon\sigma T_s^4$$

T_s is global mean surface temperature

Q is absorbed solar energy

J_S is solar constant

σ is Stefan-Boltzmann constant

H is global heat content

E is emitted longwave flux

γ is planetary co-albedo

ε is effective emissivity

At radiative "equilibrium": $$\frac{\gamma J_S}{4} = \varepsilon\sigma T_s^4$$

$$\gamma = 1 - \alpha \approx 0.7; \quad \varepsilon = \frac{\gamma J_S / 4}{\sigma T_s^4}; \quad \text{for } T_s = 288 \text{ K}, \varepsilon \approx 0.61$$

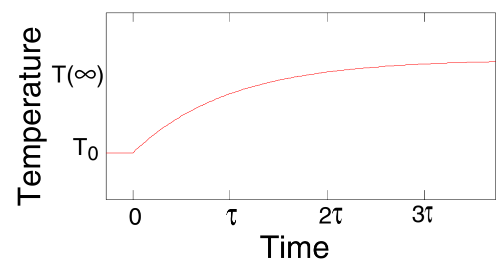
T_s, γ, and ε are properties of Earth's current climate.

CLIMATE SENSITIVITY IN ENERGY BALANCE MODEL

Global energy balance: $\frac{dH}{dt} = Q - E = \frac{\gamma J_S}{4} - \varepsilon\sigma T_s^4$

Apply step-function forcing: $F = \Delta(Q - E)$

At new "equilibrium" $\Delta T_s(\infty) = SF$



At new "equilibrium"

$$F = \left(\frac{\gamma J_S}{4} - \varepsilon\sigma T_s^4\right) - \left(\frac{\gamma_0 J_S}{4} - \varepsilon_0\sigma T_{s0}^4\right) = \frac{\partial}{\partial T_s}\left(\frac{\gamma J_S}{4} - \varepsilon\sigma T_s^4\right)\Delta T_s$$

Equilibrium sensitivity: $S \equiv \frac{\Delta T_s}{F} = \left\{\frac{\partial}{\partial T_s}\left(\frac{\gamma J_S}{4} - \varepsilon\sigma T_s^4\right)\right\}^{-1}$

NO FEEDBACK CLIMATE SENSITIVITY

In absence of feedbacks γ and ε do not depend on T_s

No-feedback sensitivity: $S_{NF} \equiv \frac{dT_s}{dQ} = \frac{dT_s}{dE} = \left(\frac{dE}{dT_s}\right)^{-1}$ for constant γ and ε.

Change in emitted flux per change in temperature:

$$\frac{dE}{dT_s} = \frac{d(\varepsilon\sigma T_s^4)}{dT_s} = 4\varepsilon\sigma T_s^3 = \frac{4}{T_s}E = \frac{4}{T_s}\frac{\gamma J_S}{4} = \frac{\gamma J_S}{T_s}$$

$$S_{NF} = \frac{T_s}{\gamma J_S}$$

$J_S = 1368\ \mathrm{Wm^{-2}}$; $T_s = 288$ K; $\gamma = 0.7$; $S_{NF} = 0.30\ \mathrm{K/(Wm^{-2})}$

$$\Delta T_{2\times} = F_{2\times}S_{NF} = 3.7\ \mathrm{Wm^{-2}} \times 0.30\ \mathrm{K/(Wm^{-2})} = 1.1\ \mathrm{K}$$

CLIMATE SENSITIVITY INCLUDING FEEDBACKS

With feedbacks γ and ε may change with changing T_s

Equilibrium climate sensitivity

$$S = \frac{T_s}{\gamma_0 J_S} \frac{1}{\left(1 - \frac{1}{4} \frac{d\ln\gamma}{d\ln T_s}\Big|_0 + \frac{1}{4} \frac{d\ln\varepsilon}{d\ln T_s}\Big|_0\right)} \quad \mathrm{K/(W\ m^{-2})}$$

f is feedback ***factor***

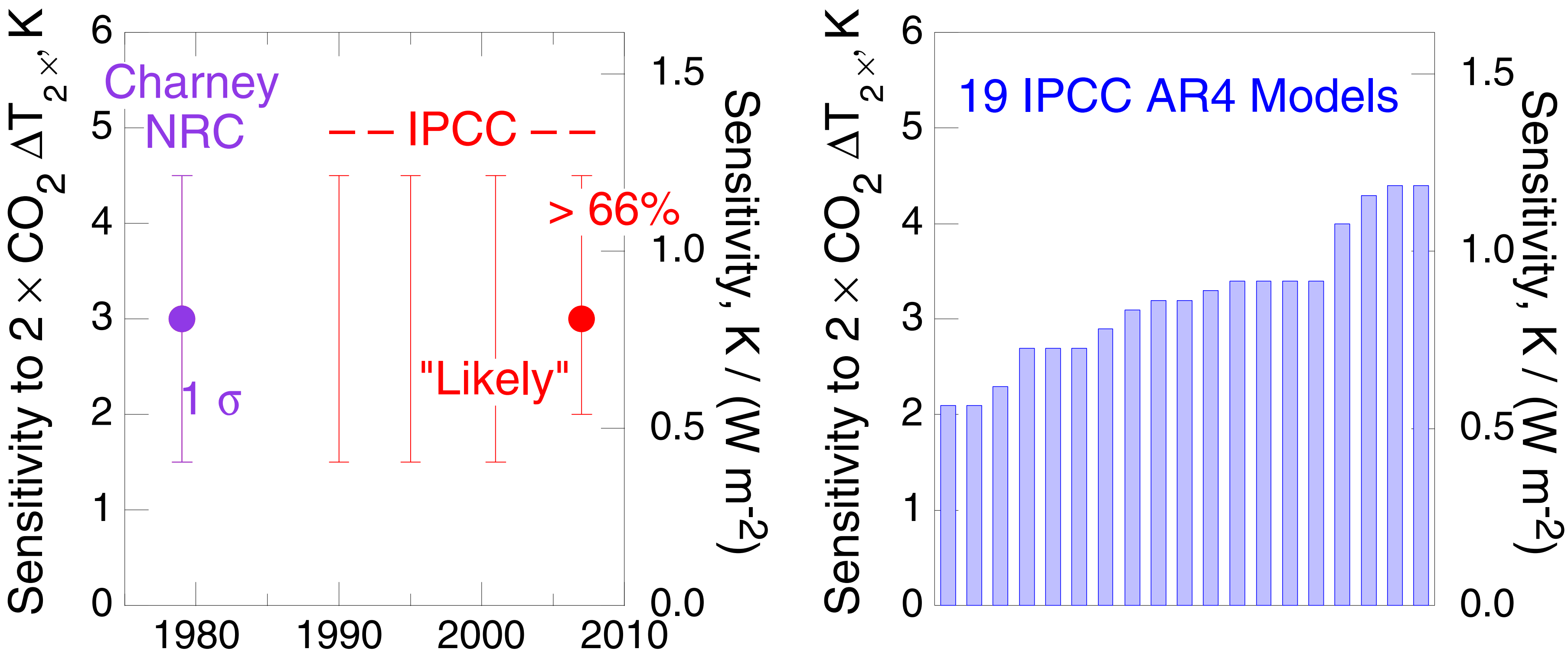
$$f = \frac{1}{\left(1 - \frac{1}{4} \frac{d\ln\gamma}{d\ln T_s}\Big|_0 + \frac{1}{4} \frac{d\ln\varepsilon}{d\ln T_s}\Big|_0\right)} = \frac{1}{1 - \Phi}$$

Φ is feedback ***strength***

Sensitivity, feedback factor, feedback strength are all ***properties of Earth's present climate system*** (just like γ and ε).

ESTIMATES OF EARTH'S CLIMATE SENSITIVITY AND ASSOCIATED UNCERTAINTY

Major national and international assessments and current climate models

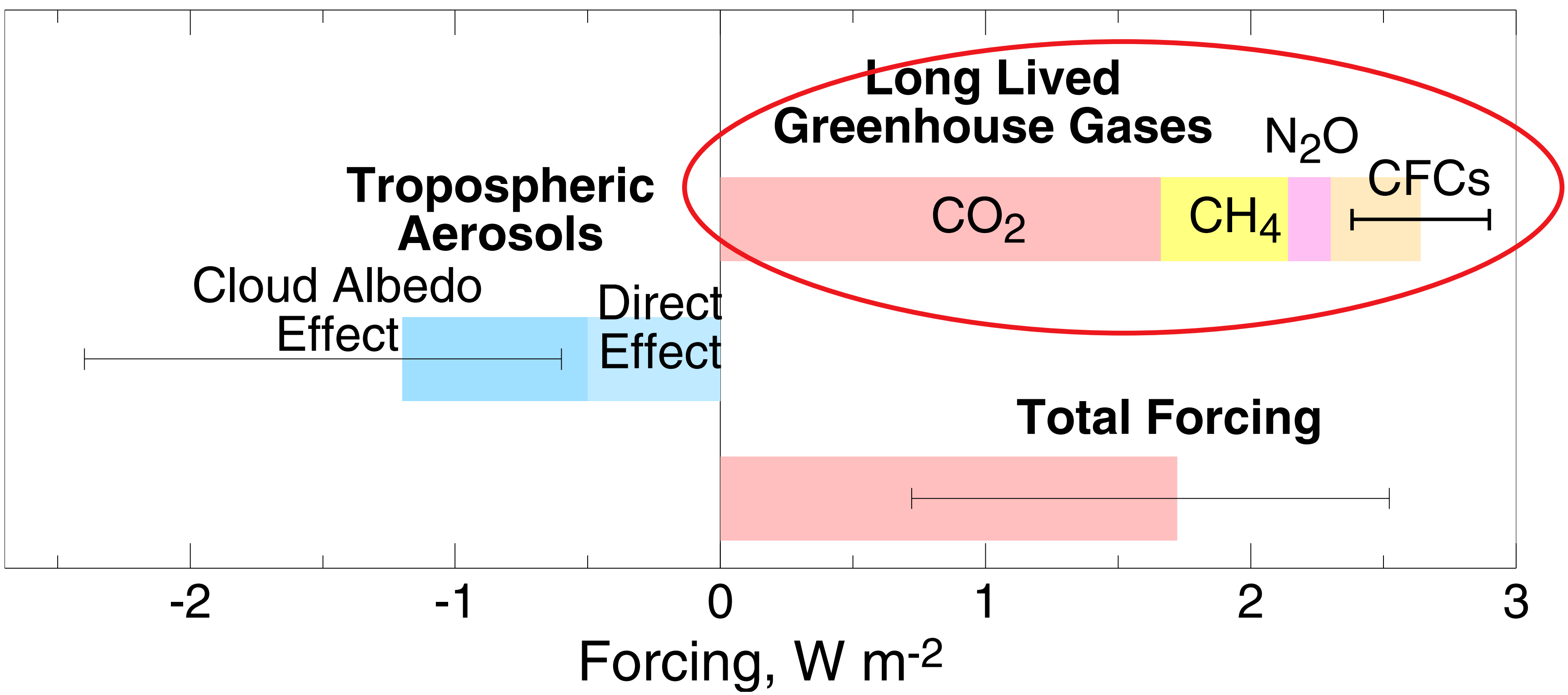


Current estimates of Earth's climate sensitivity are centered about a CO_2 doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty.

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

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

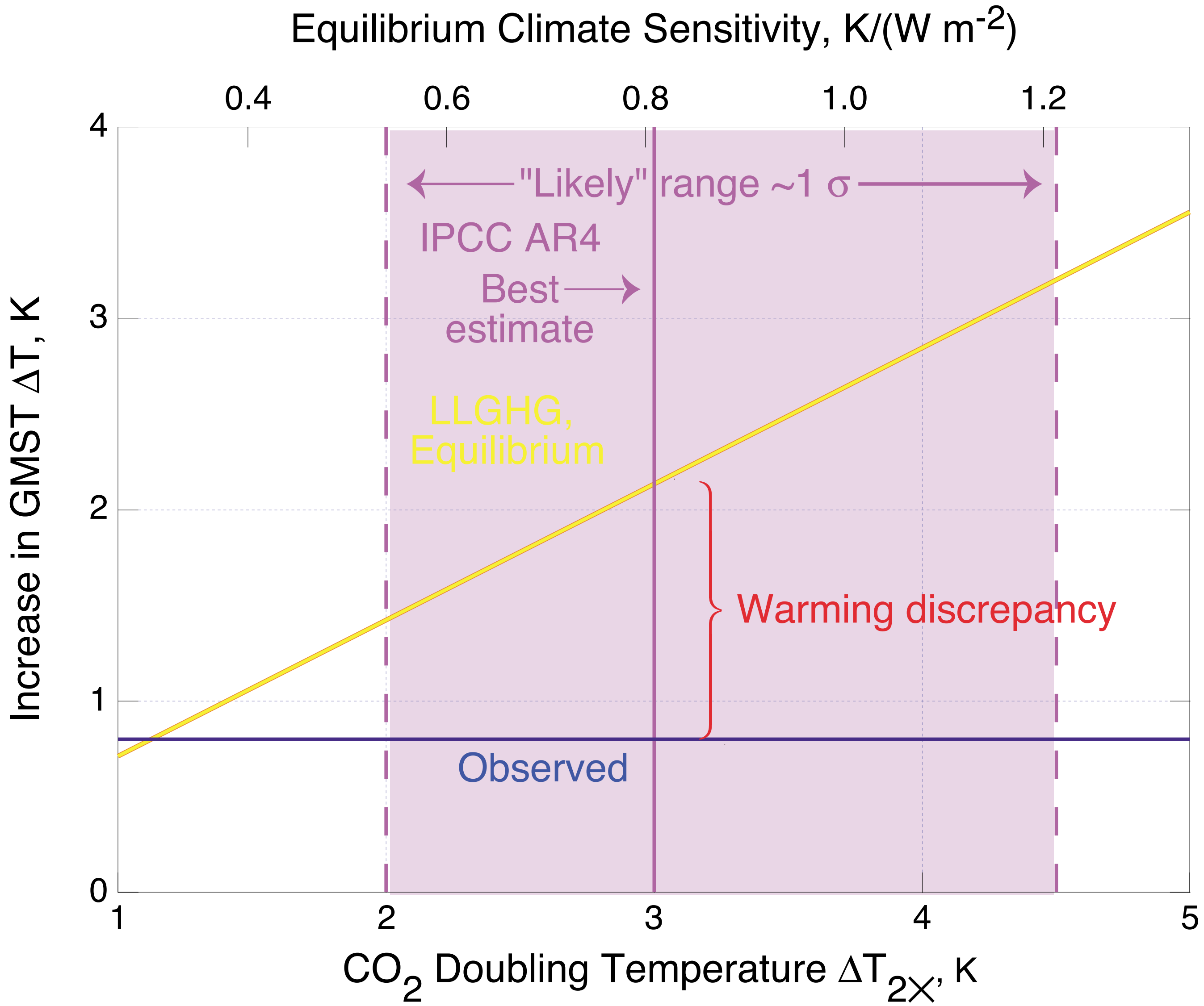
Extracted from IPCC AR4 (2007)



Total forcing includes other anthropogenic and natural (solar) forcings. Forcing by tropospheric ozone, ~0.35 W m^{-2}, is the greatest of these.

EXPECTED INCREASE IN GLOBAL TEMPERATURE

Long-lived GHGs only – Dependence on climate sensitivity



Ramanathan, PNAS 2008

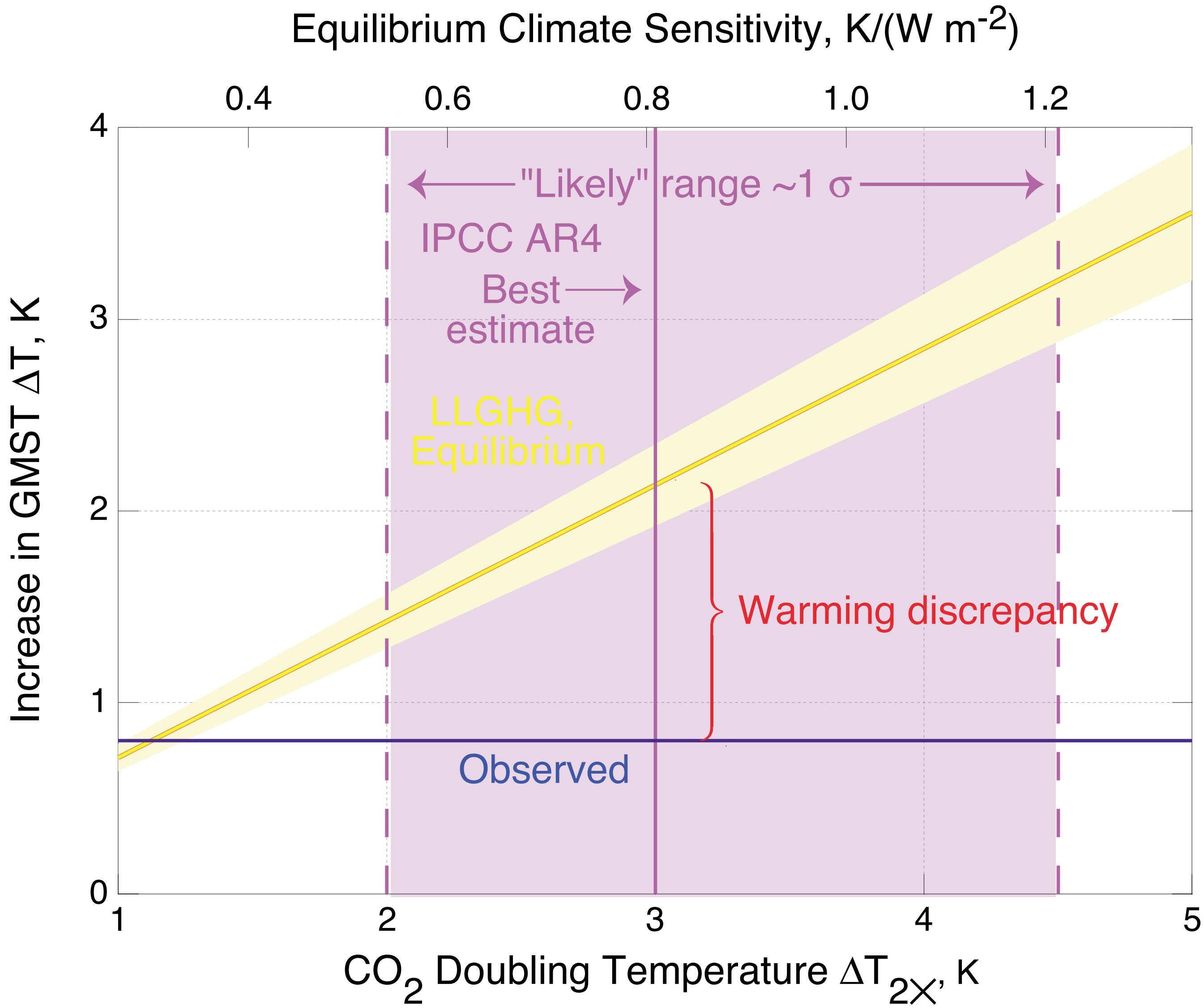
This discrepancy holds throughout the IPCC AR4 "likely" range for climate sensitivity.

UNCERTAINTY IN GREENHOUSE GAS FORCING

± 10%, 2 σ – IPCC

EXPECTED INCREASE IN GLOBAL TEMPERATURE

Long-lived GHGs only – Dependence on climate sensitivity

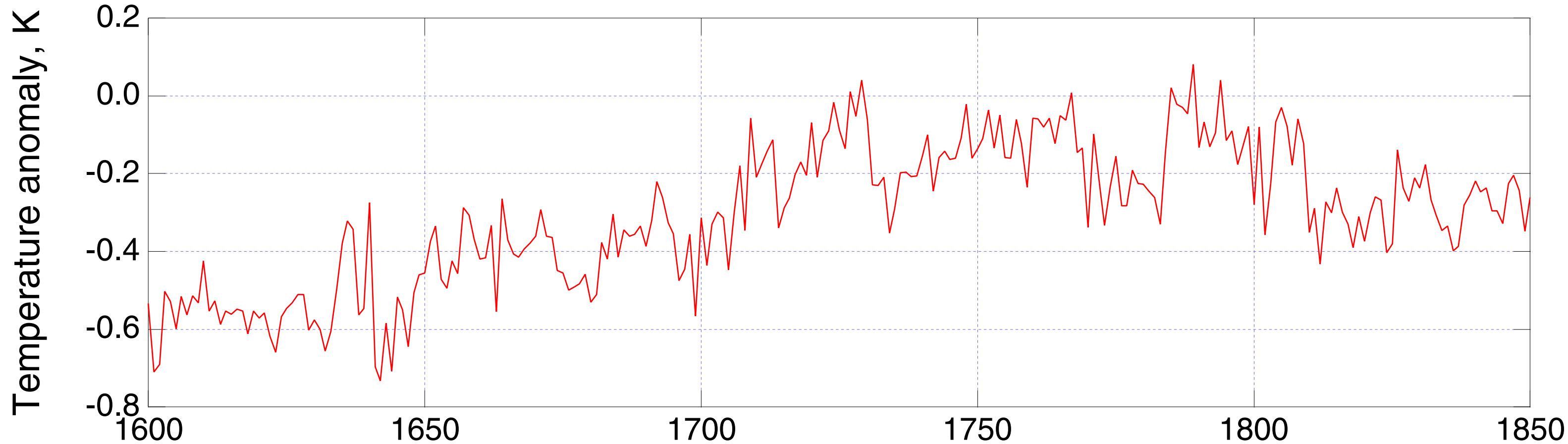


Little of the warming discrepancy is resolved by uncertainty in GHG forcing.

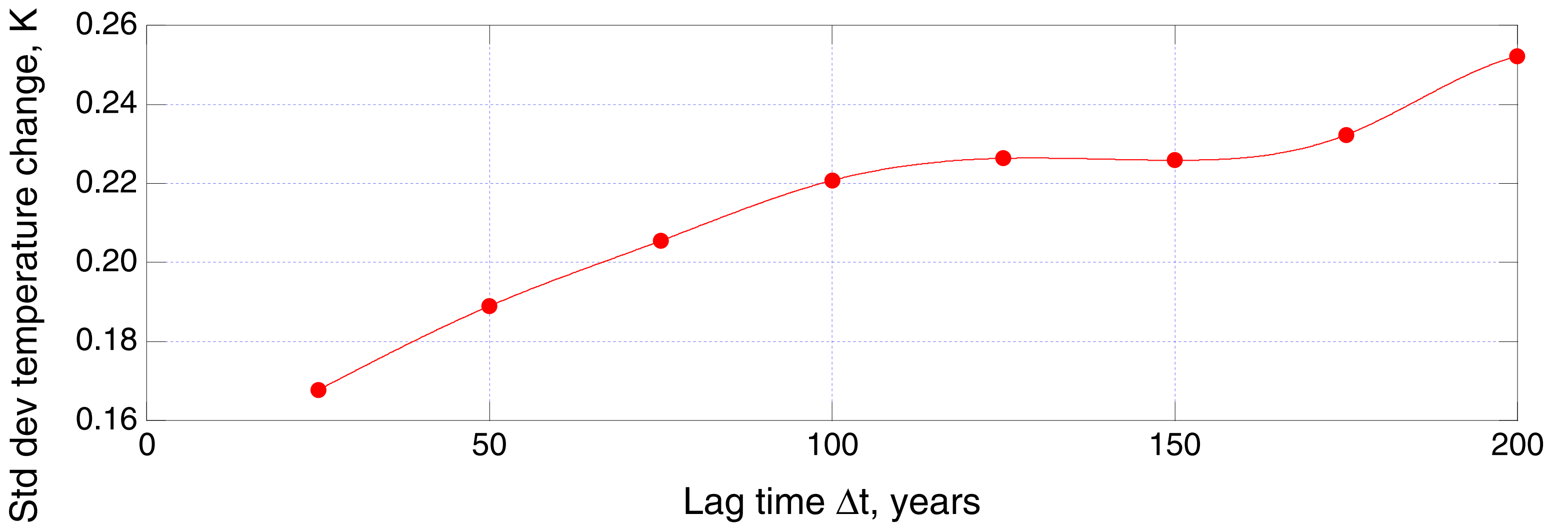
COUNTERVAILING NATURAL COOLING OFFSETTING EXPECTED WARMING

ESTIMATING NATURAL VARIABILITY

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



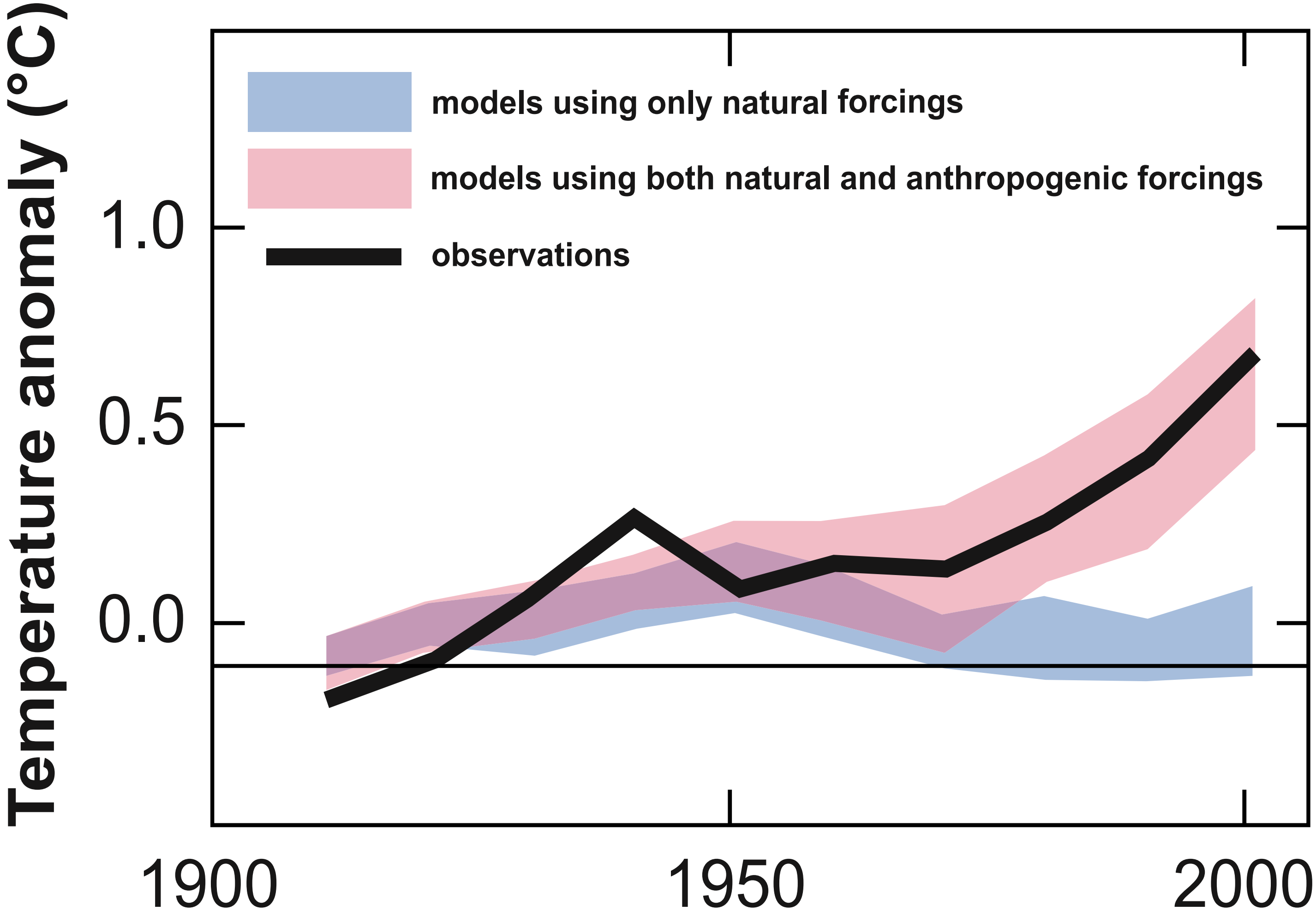
Juckes et al., Climate of the Past, 2007



Typical variation in temperature over 150 years ~ 0.2 K.

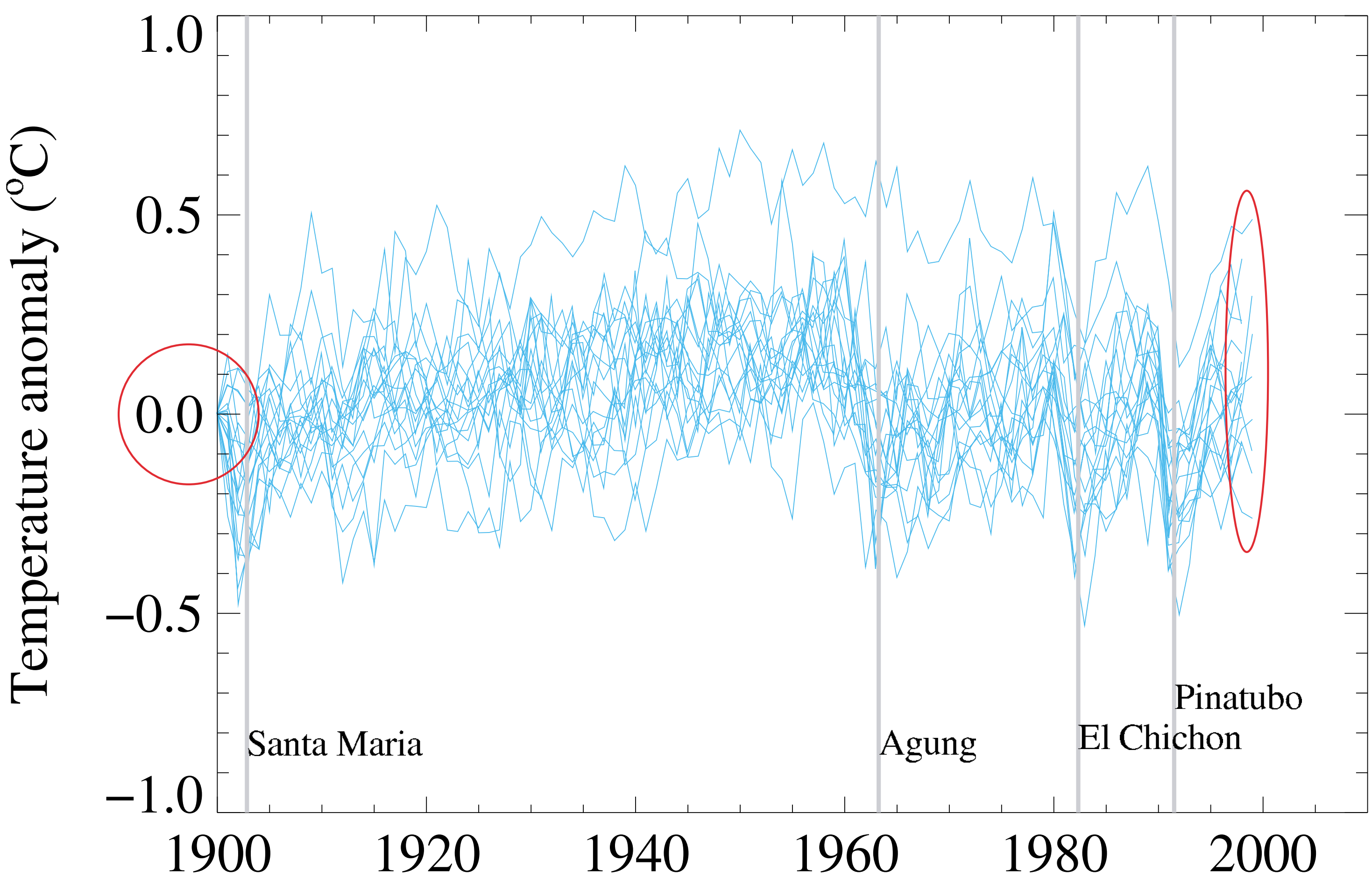
ESTIMATING NATURAL VARIABILITY

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



ESTIMATING NATURAL VARIABILITY

Anomaly relative to 1900; 5 Models, 19 runs, from IPCC AR4

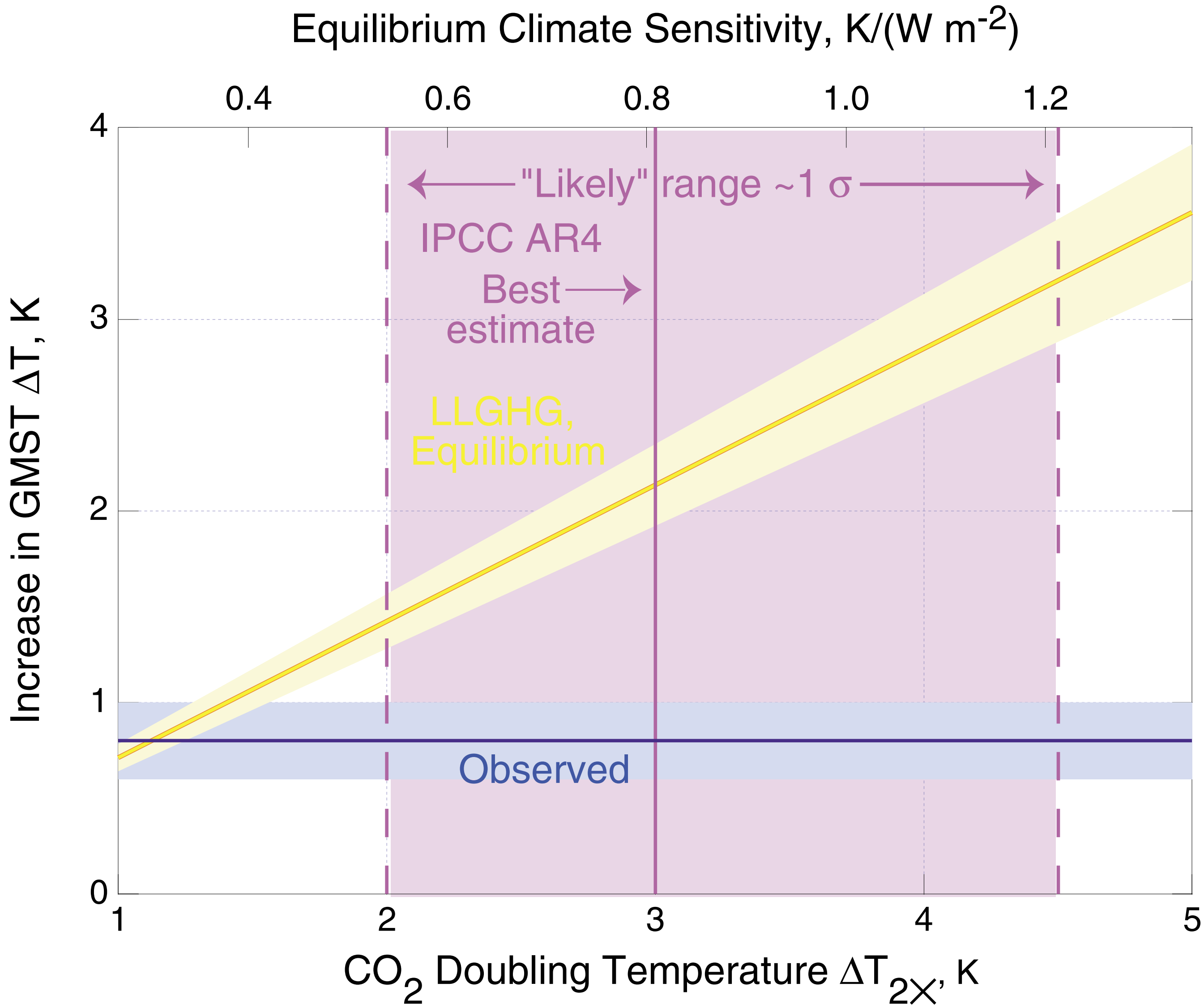


IPCC AR4

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

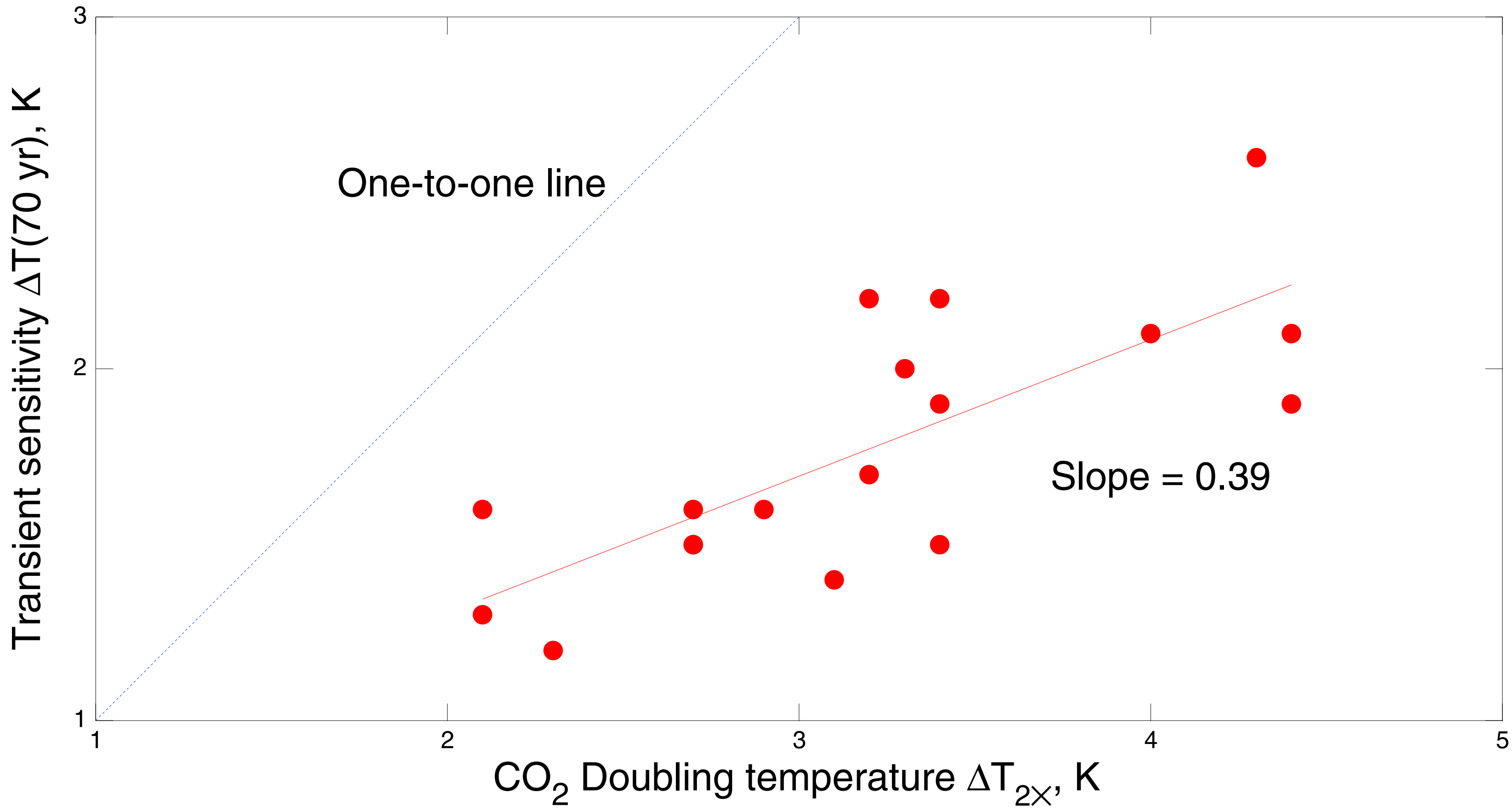


The warming discrepancy cannot be resolved by countervailing natural cooling over the industrial period.

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



Transient sensitivity in models is only about 40% of equilibrium sensitivity.

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

ACCOUNTING FOR DISEQUILIBRIUM

Upon application of a forcing to climate initially at equilibrium

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

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

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

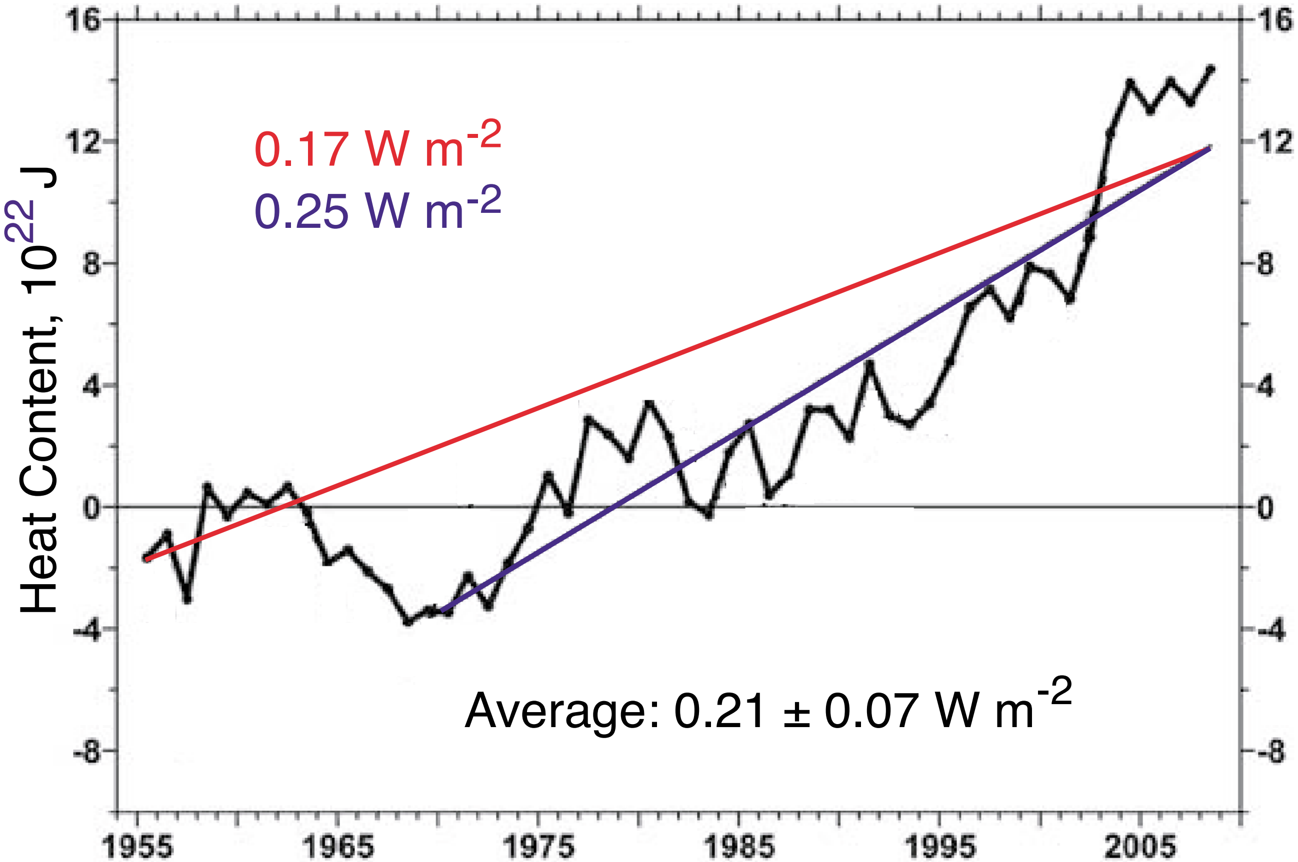
Determine global heating rate from increase in heat content of global ocean.

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



Levitus et al., GRL, 2009

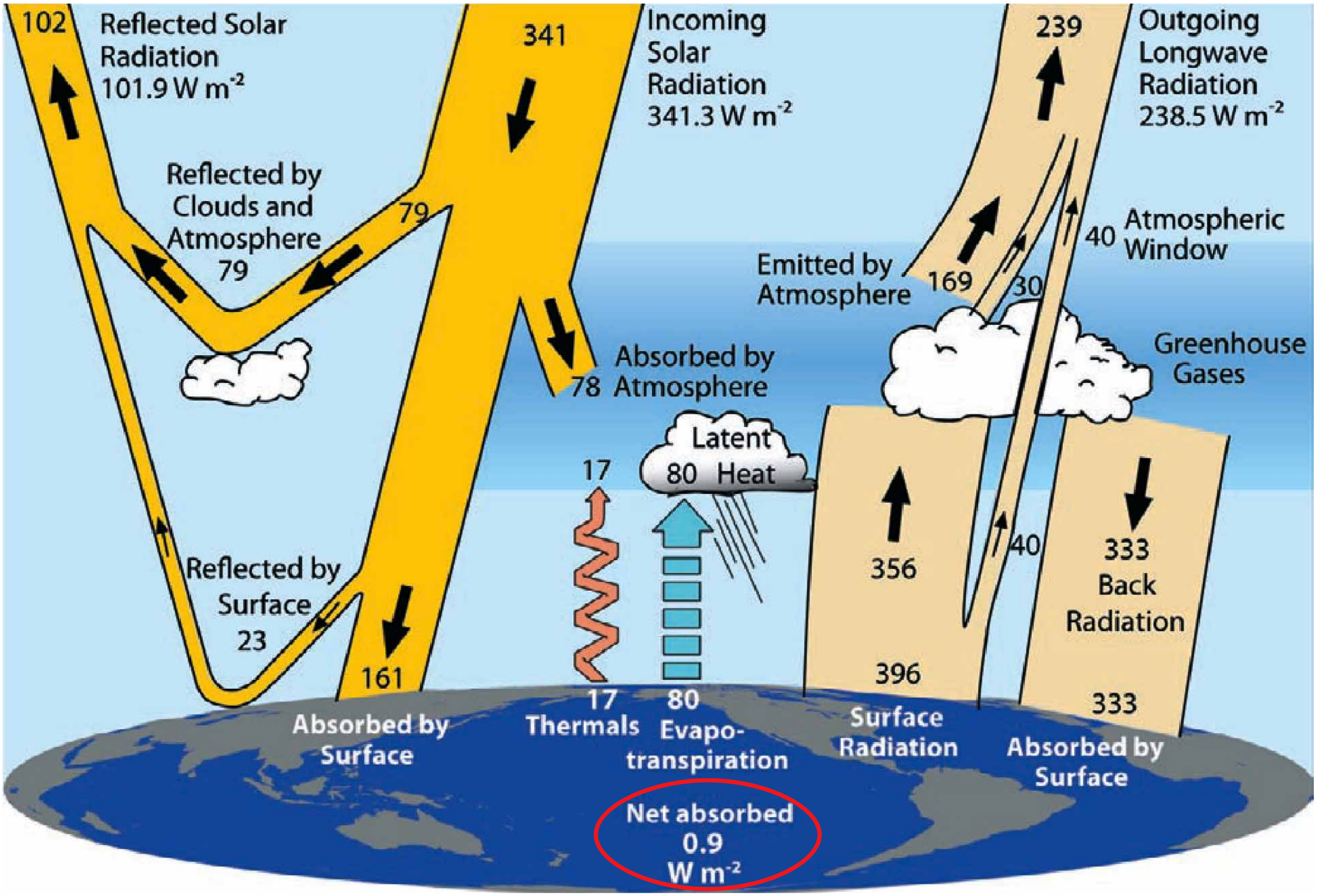
Accounting for heat to 3 km: factor of 1.44.

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

Total heating rate 0.37 ± 0.12 W m^{-2}.

GLOBAL ANNUAL ENERGY BUDGET

Fluxes in W m^{-2}

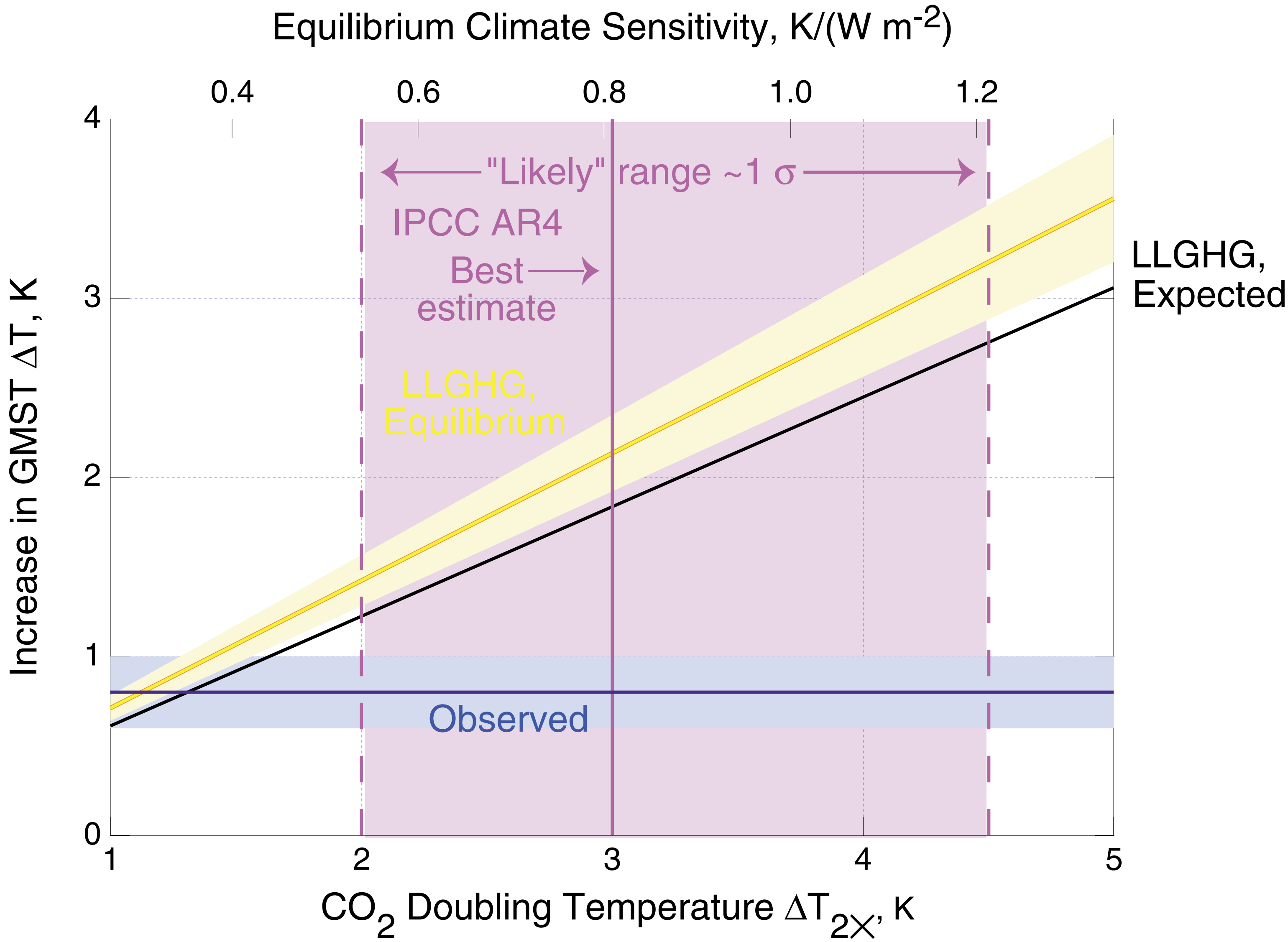


Trenberth, Fasullo, Kiehl, BAMS, 2008

Note energy imbalance, 0.9 W m^{-2} inferred from ocean heating rate.

EXPECTED INCREASE IN GLOBAL TEMPERATURE

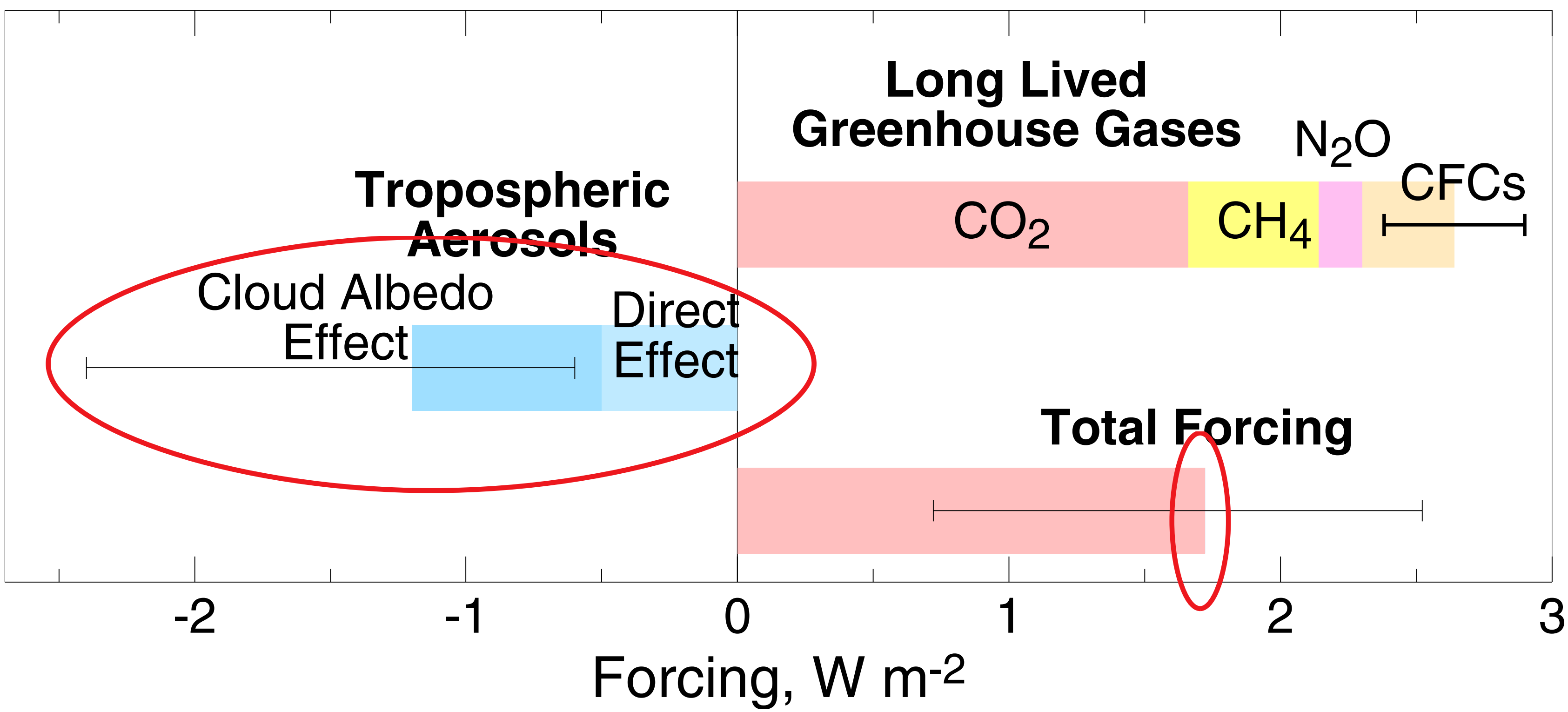
Long-lived GHGs only – Dependence on climate sensitivity



Little of the warming discrepancy can attributed to thermal disequilibrium.

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

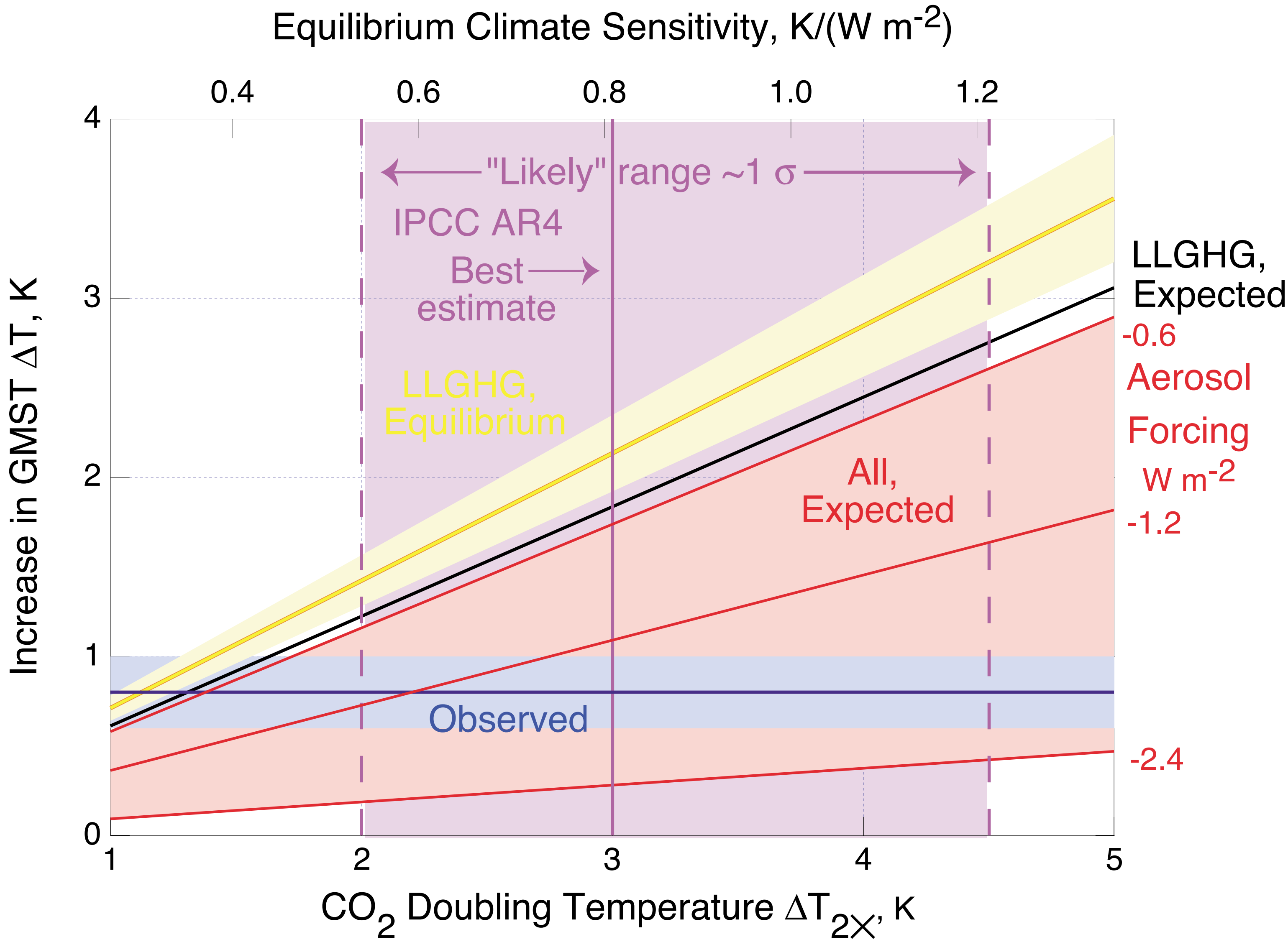
Extracted from IPCC AR4 (2007)



Total forcing includes other anthropogenic and natural (solar) forcings. Forcing by tropospheric ozone, ~0.35 W m^{-2}, is the greatest of these.

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.

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?

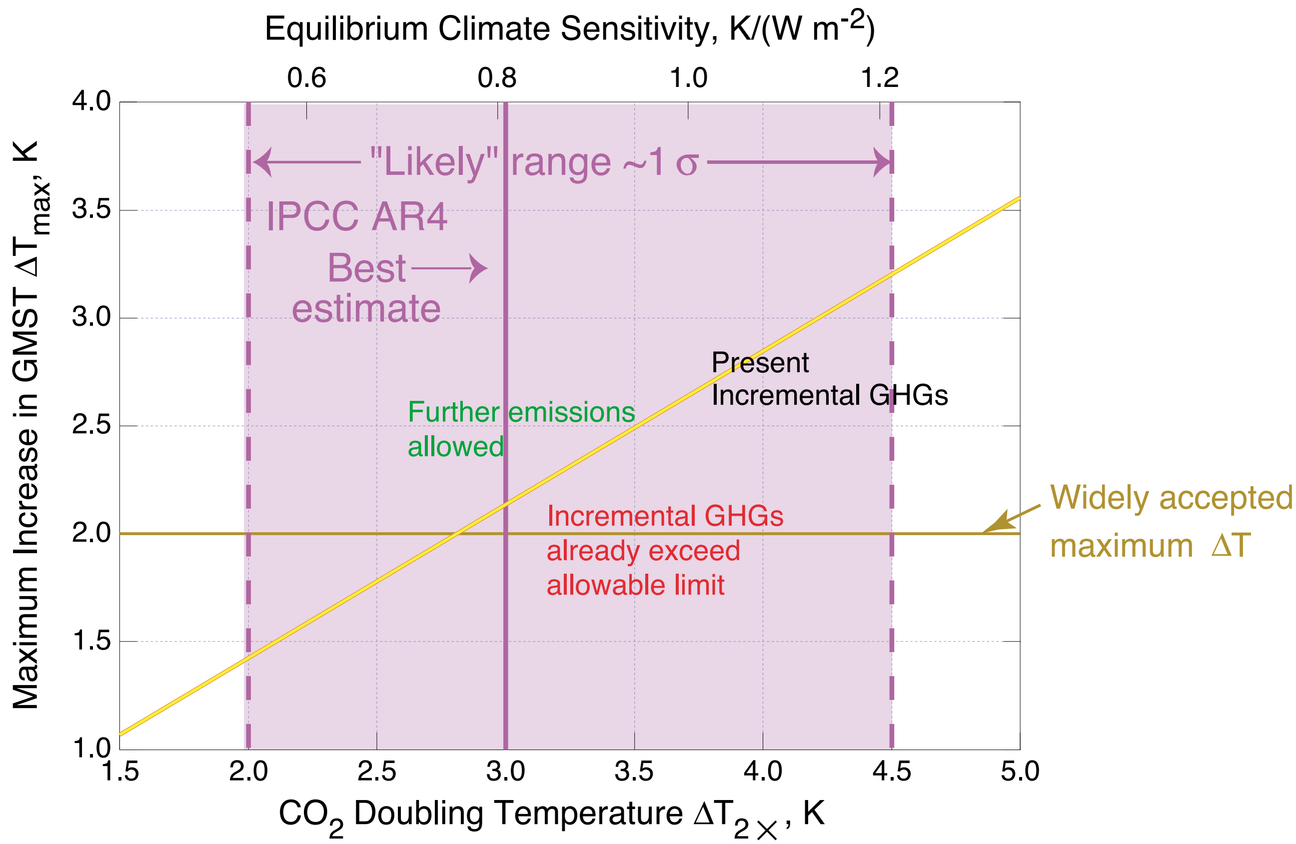
Answer depends on target threshold and climate sensitivity.

Premise of the calculation:

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

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 $\Delta T_{2\times} < 3$ K, further emissions are allowed without exceeding ΔT_{max}.

If $\Delta T_{max} < 2.1$ K and/or sensitivity $\Delta T_{2\times} > 3$ K, committed temperature increase already exceeds ΔT_{max}.

MAXIMUM ALLOWABLE CO_2 MIXING RATIO

$$\begin{array}{l}\text{Max } \Delta\ CO_2 \\ \text{mixing ratio}\end{array} = \left(\begin{array}{l}\text{Max} \\ \Delta \text{ temp}\end{array} - \begin{array}{l}\text{Current} \\ \text{committed} \\ \Delta \text{ temp}\end{array} \right) / \left(\text{Sensitivity} \times \begin{array}{l}\text{Forcing} \\ \text{per } \Delta\ CO_2\end{array} \right)$$

$$\Delta m_{CO_2} = (\Delta T_{max} - \Delta T_c) / Sf$$

$$\Delta m_{CO_2} = \Delta T_{max} / Sf - F_c / f$$

$$f \approx F_{2\times} / m_c \ln 2 = 0.014 \text{ W m}^{-2} \text{ ppm}^{-1}$$

ALLOWABLE FUTURE CO_2 EMISSIONS

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

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

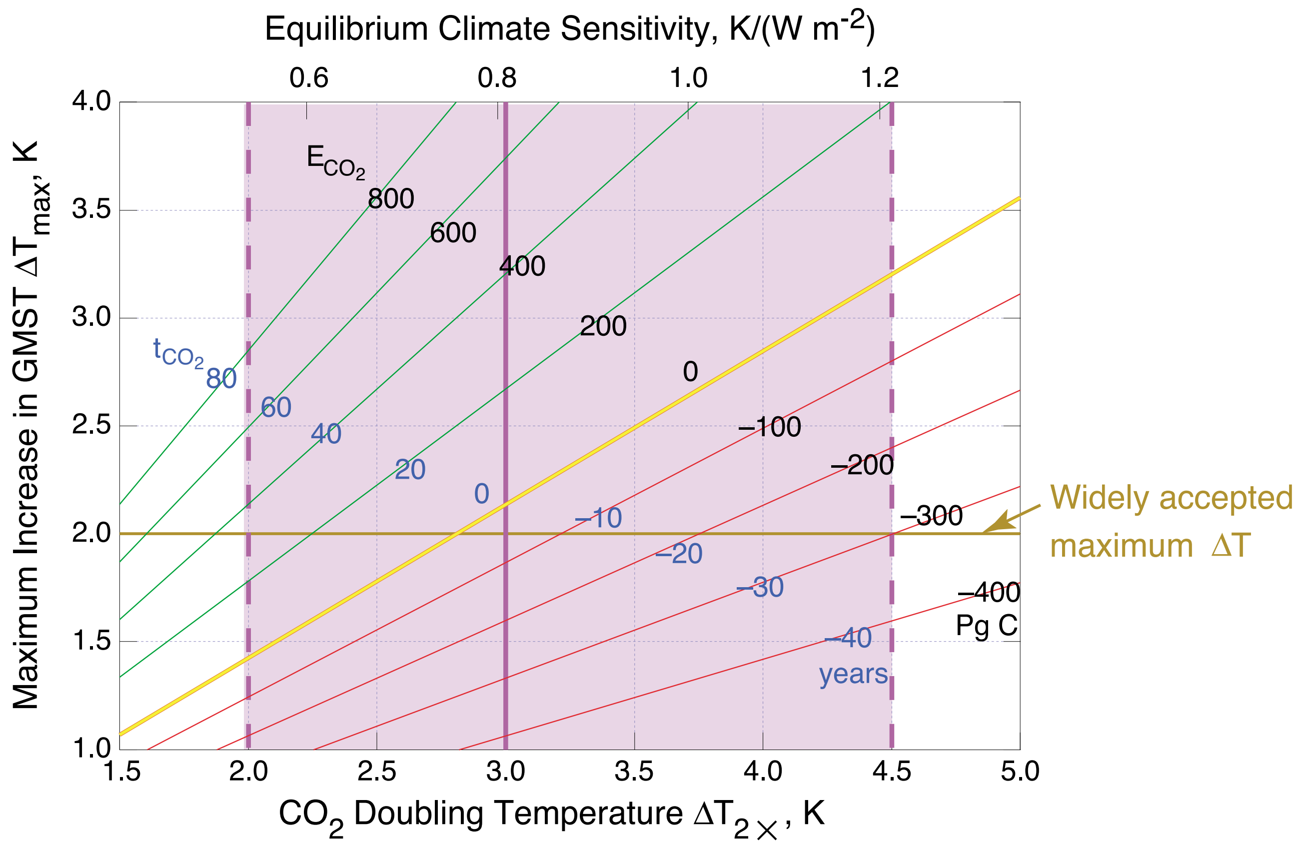
HOW LONG CAN WE CONTINUE TO EMIT CO_2 AT THE PRESENT RATE?

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



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

If sensitivity $\Delta T_{2\times}$ is 3 K, ***no more emissions***.

If sensitivity $\Delta T_{2\times}$ is 2 K, ~ ***30 more years of emissions at present rate***.

If sensitivity $\Delta T_{2\times}$ is 4.5 K, ***threshold is exceeded by ~30 years***.

APPROACHES TO DETERMINING CLIMATE SENSITIVITY

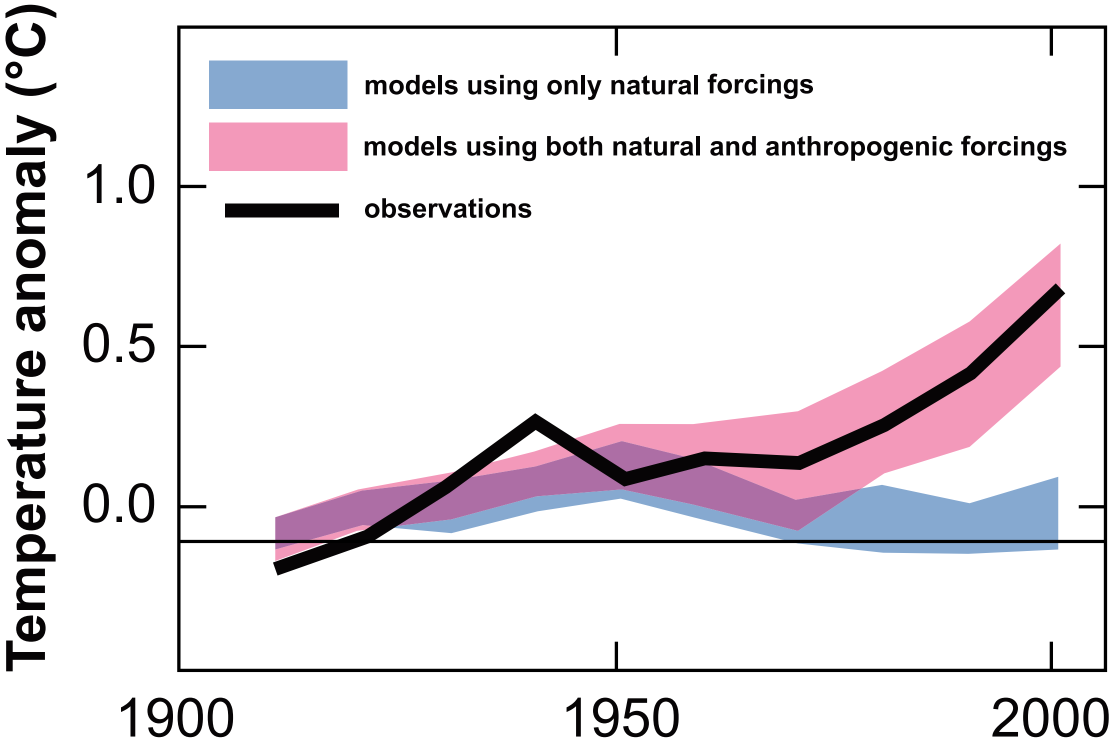
Climate models

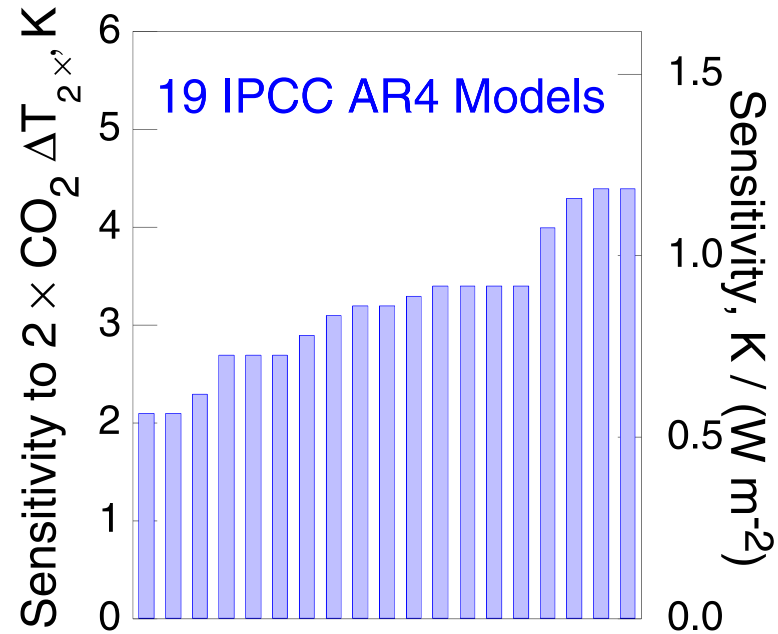
Empirical

- Paleo: Concerns over accuracy
- Sensitivity = Time constant/Heat Capacity
- Instrumental record

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models





“ 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***.

IPCC AR4, 2007

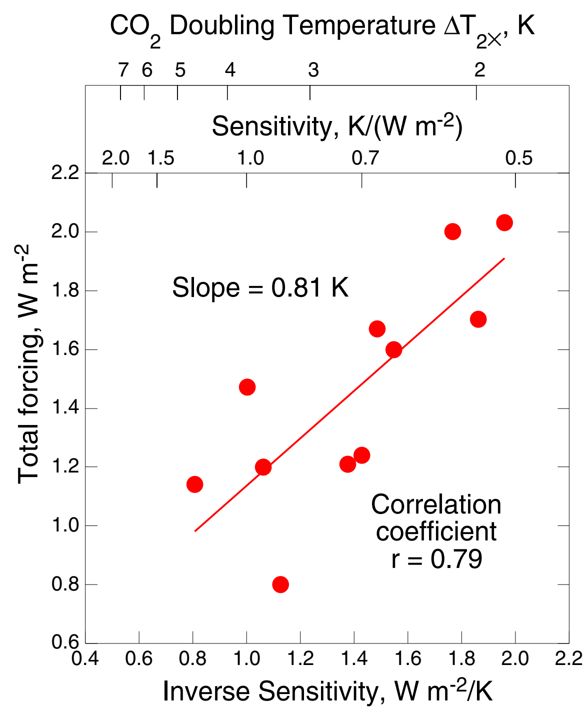
How can this be?

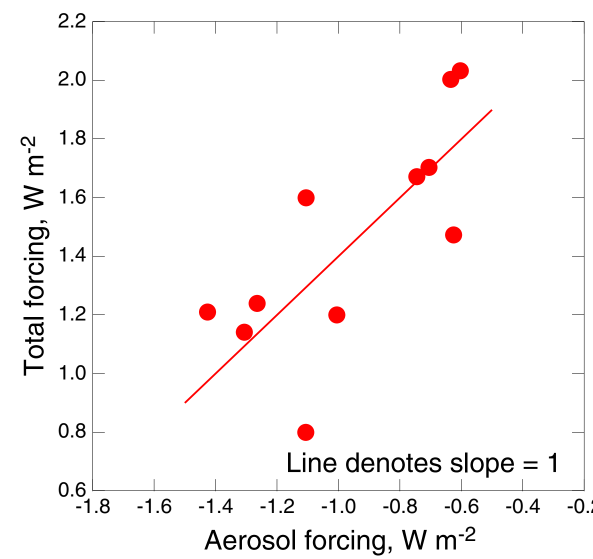
CORRELATION OF AEROSOL FORCING, TOTAL FORCING, AND SENSITIVITY IN CLIMATE MODELS

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.

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

EMPIRICAL DETERMINATION OF CLIMATE SENSITIVITY

From known forcing, temperature change, and heating rate

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

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

or

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

.

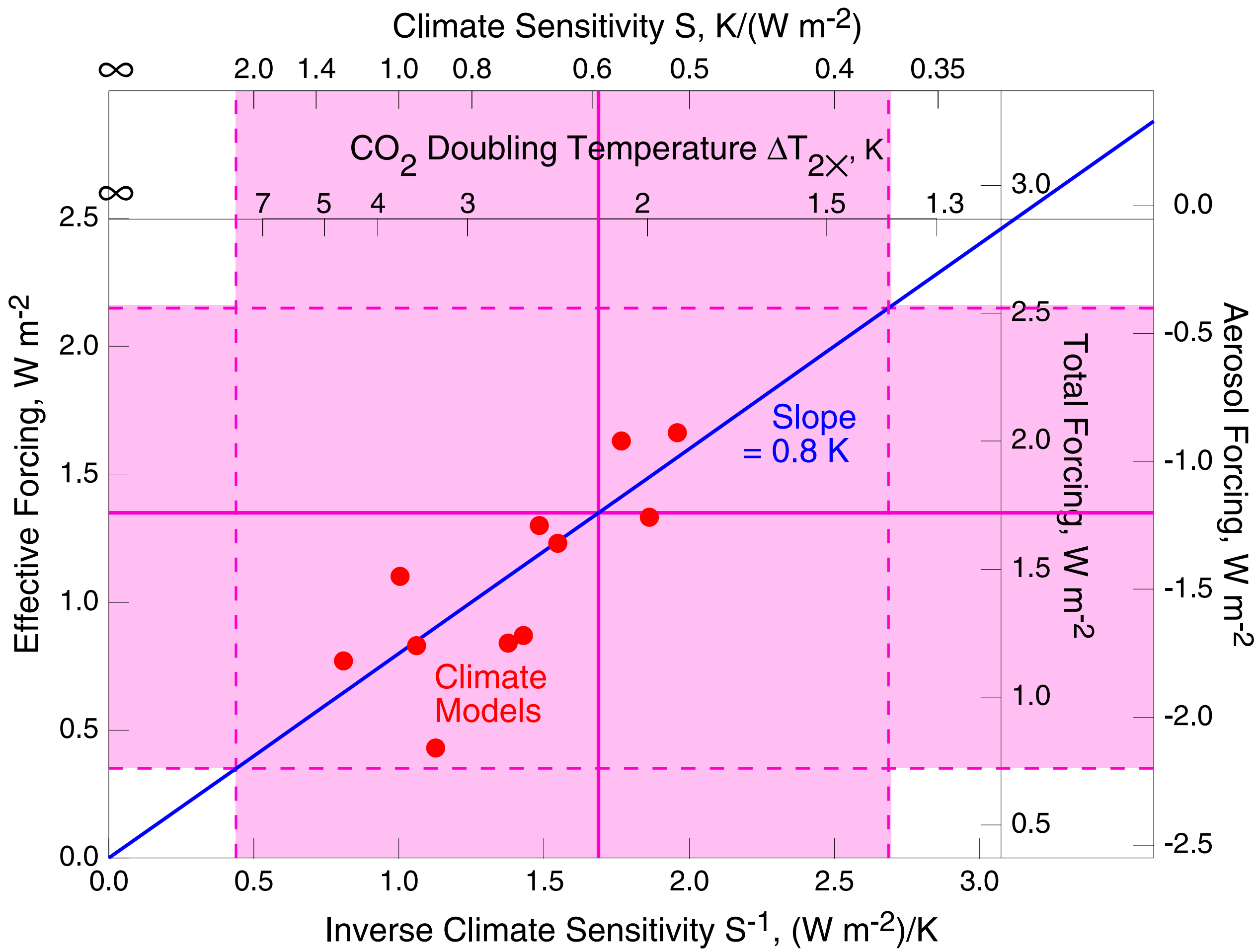
CLIMATE MODEL DETERMINATION OF CLIMATE SENSITIVITY

Effect of uncertainty in forcing

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

$$\Delta T = S F_{\text{eff}}$$

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



Uncertainty in aerosol forcing allows climate models with widely differing sensitivities to reproduce temperature increase over industrial period.

SUMMING UP TO HERE

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

Confident determination of climate sensitivity requires ***great reduction in uncertainty in aerosol forcing*** over the industrial period.

THE PATH FORWARD

Determine aerosol forcing with high accuracy.

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***.

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***.