WHY HASN'T EARTH WARMED AS MUCH AS EXPECTED?

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ATMOSPHERIC RADIATION

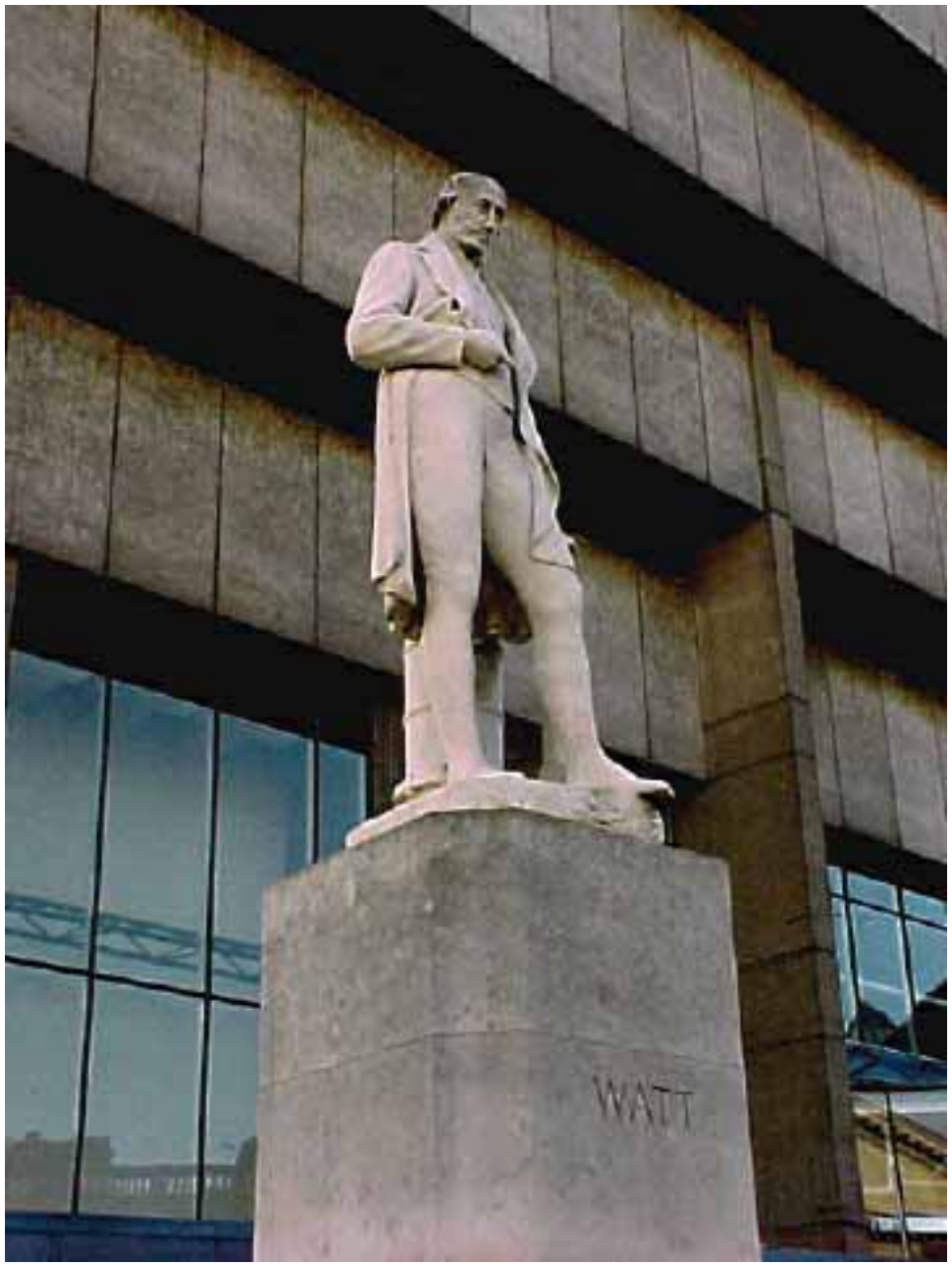
Power per area

Energy per time per area

Unit:

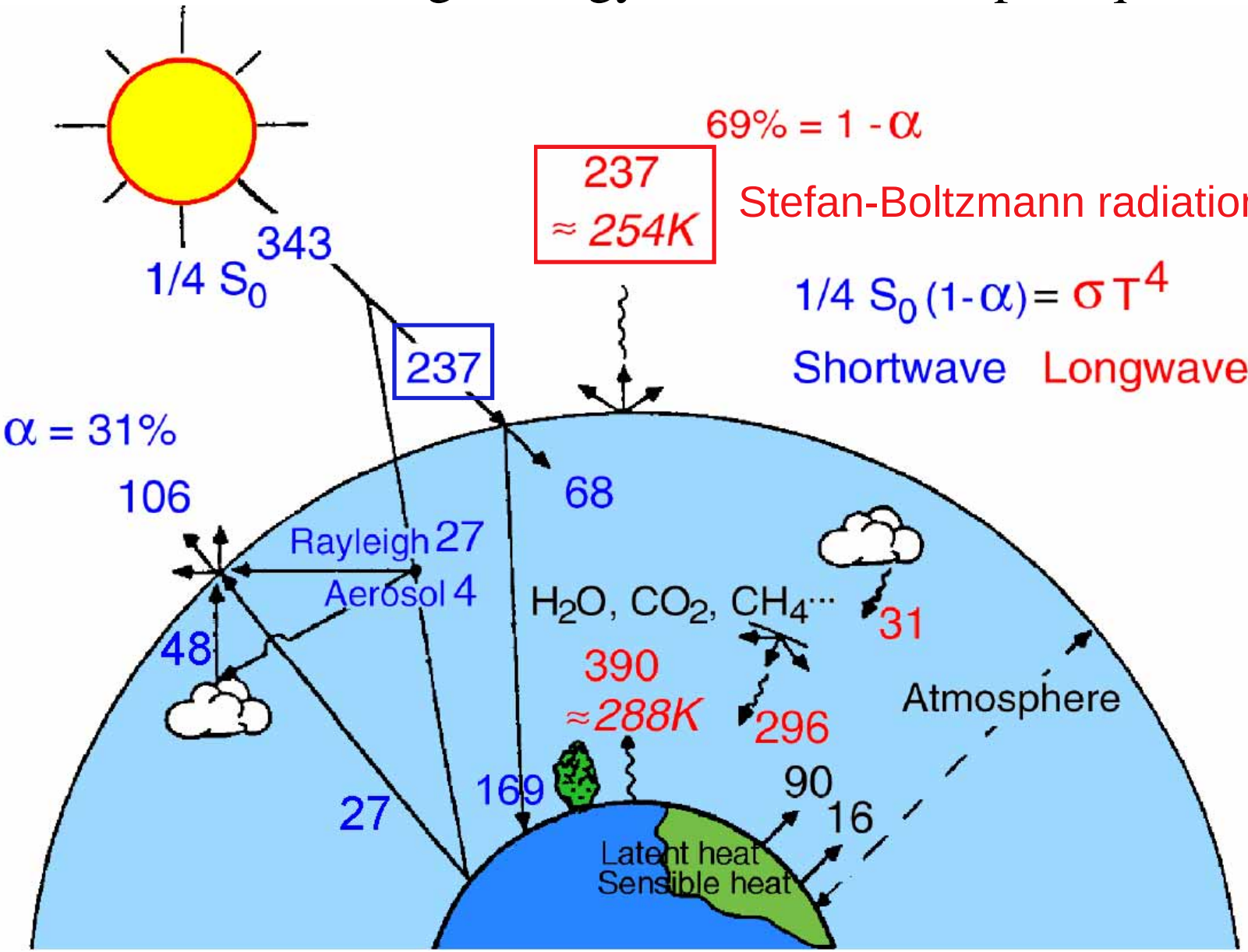
Watt per square meter

$W\ m^{-2}$



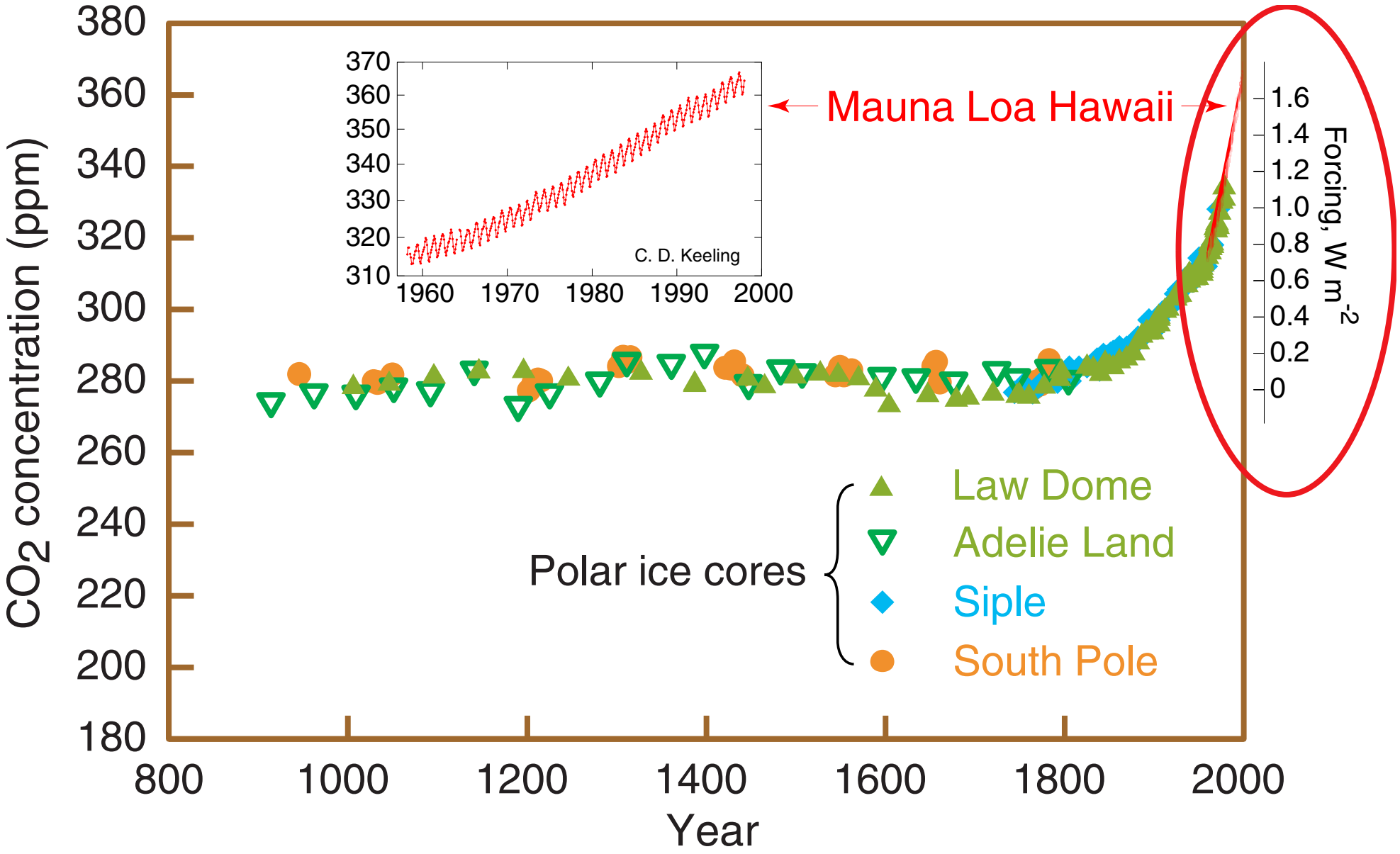
GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

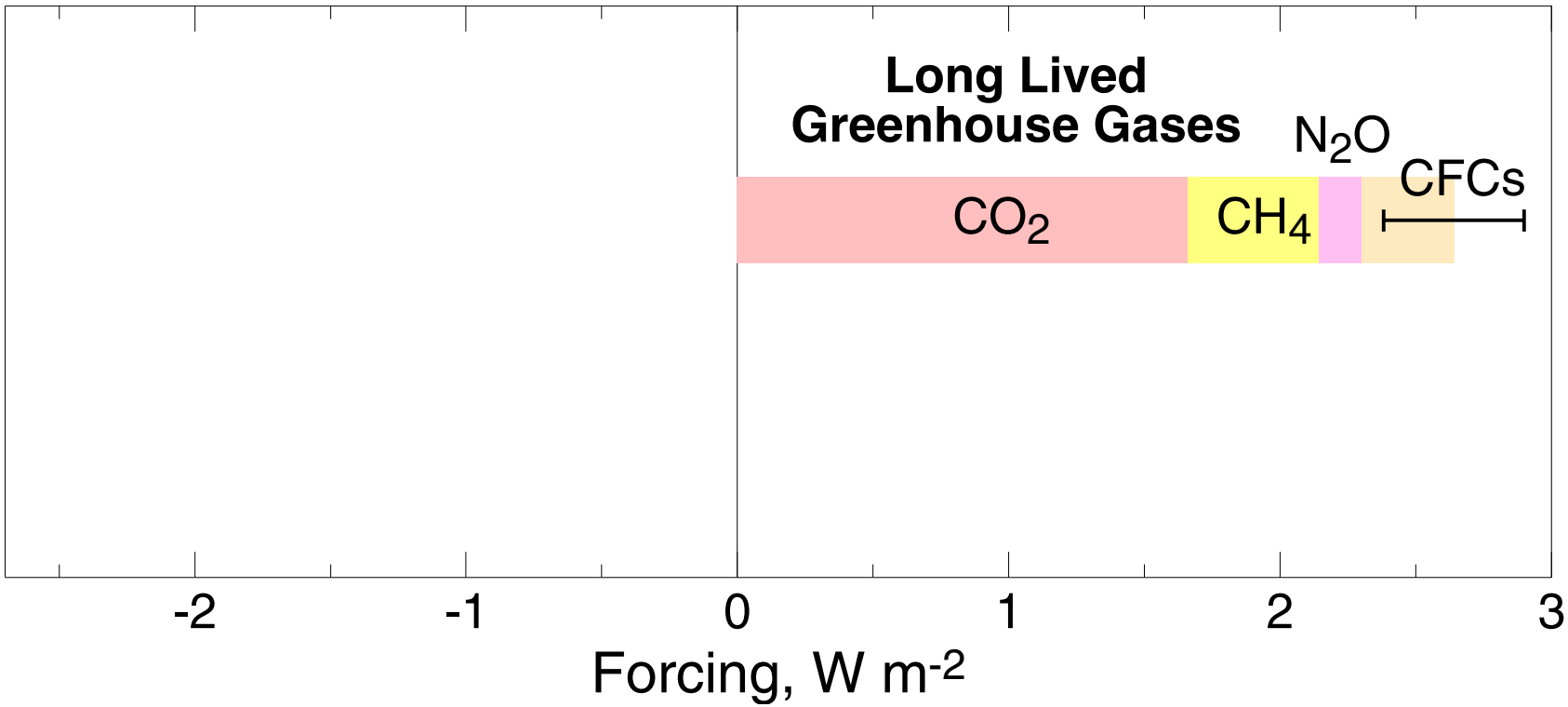
ATMOSPHERIC CARBON DIOXIDE IS INCREASING



Global carbon dioxide concentration and infrared radiative forcing over the last thousand years

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)

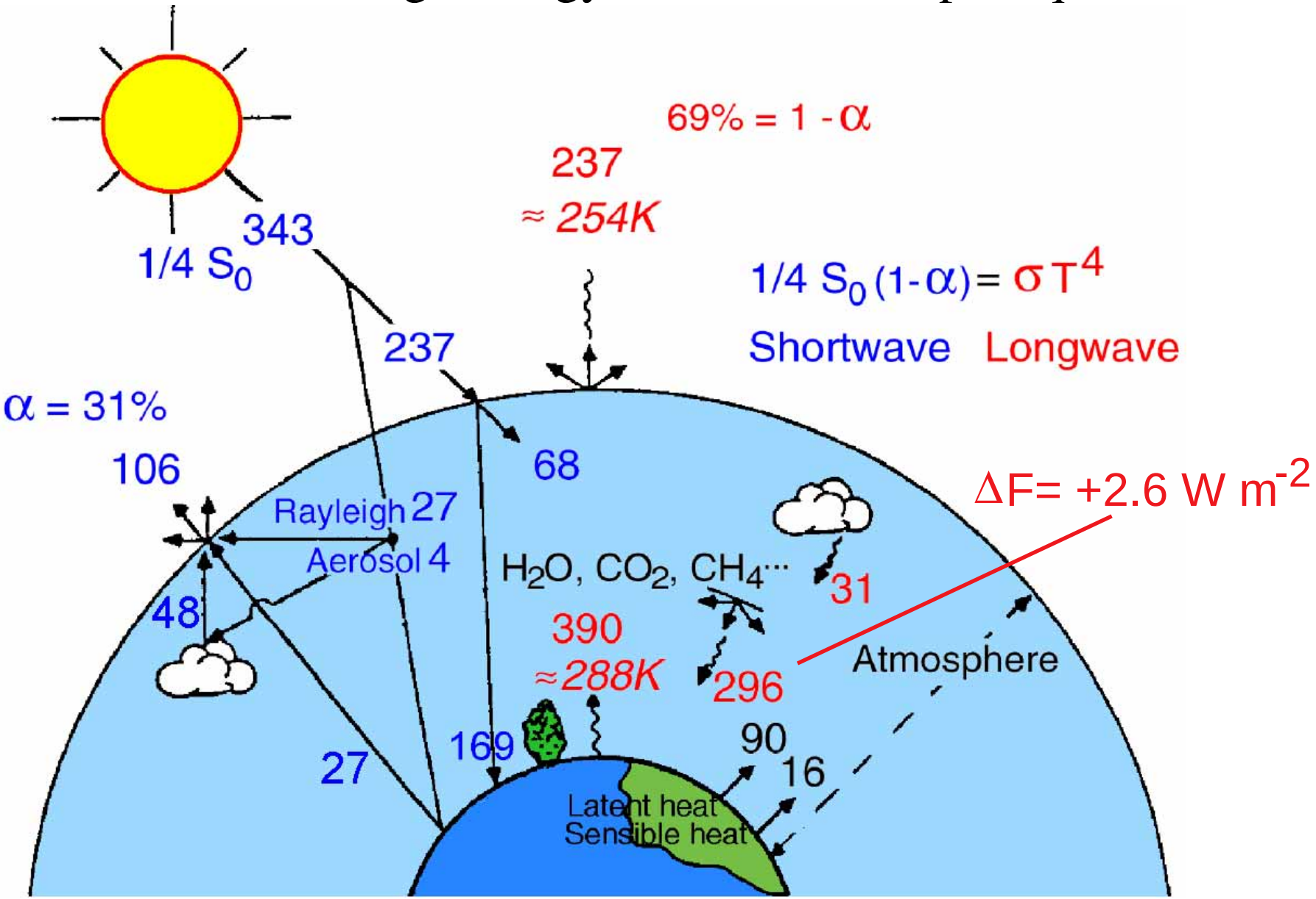


Greenhouse gas forcing is considered accurately known.

Gases are uniformly distributed; radiation transfer is well understood.

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

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"

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

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

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

IPCC, 2007
Best Estimate

Expected temperature increase:

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

Warming
Discrepancy

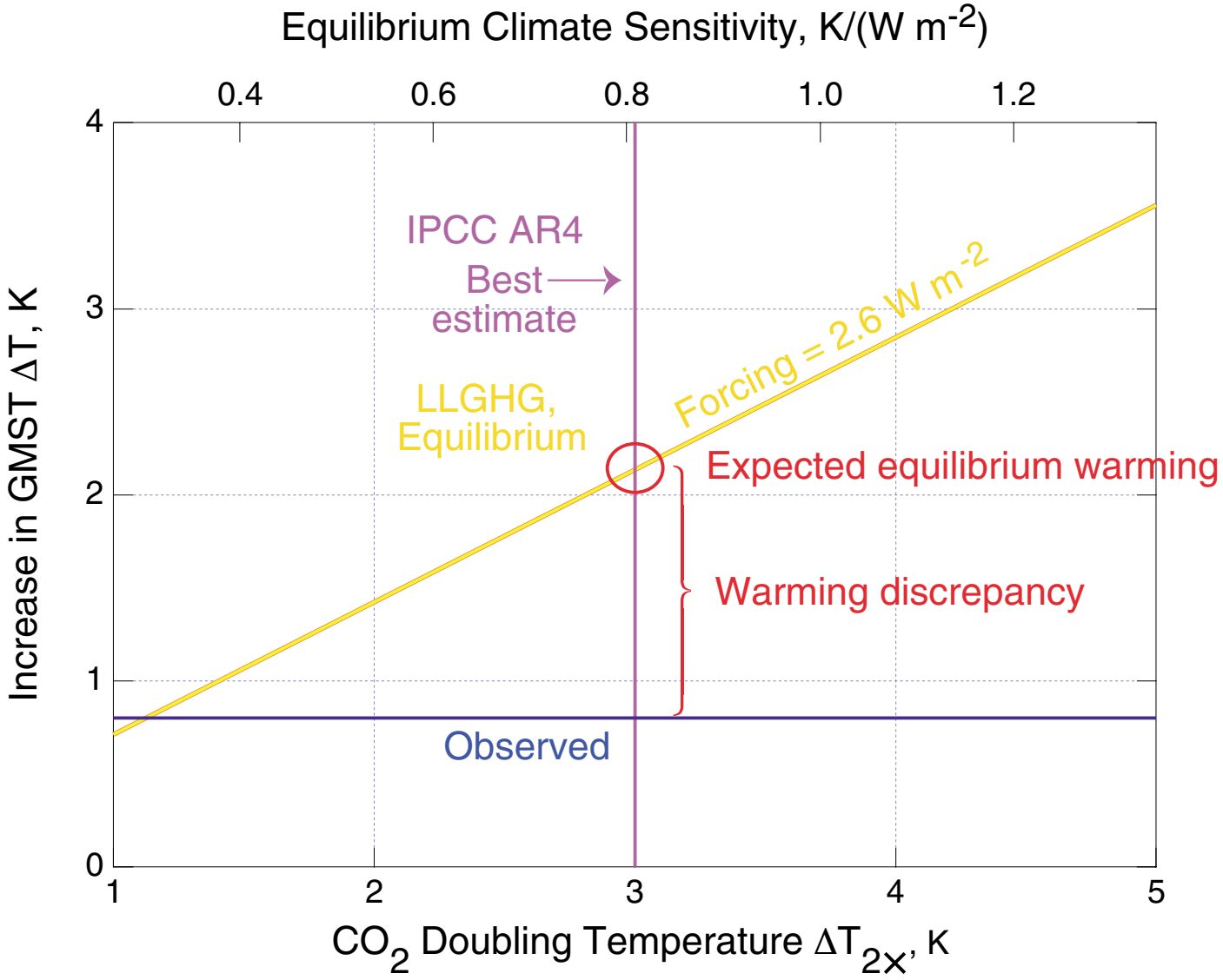
Observed temperature increase:

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

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

EXPECTED INCREASE IN GLOBAL TEMPERATURE

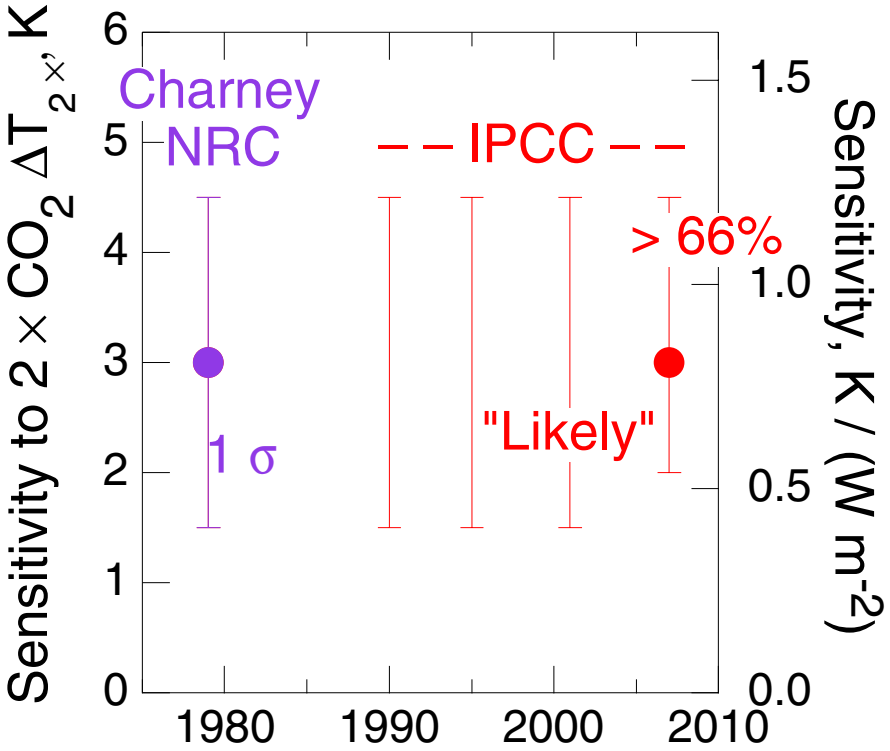
Long-lived GHGs only – Dependence on climate sensitivity



Warming discrepancy denotes the expected warming that has not occurred: ~60% of the expected warming.

ESTIMATES OF EARTH'S CLIMATE SENSITIVITY AND ASSOCIATED UNCERTAINTY

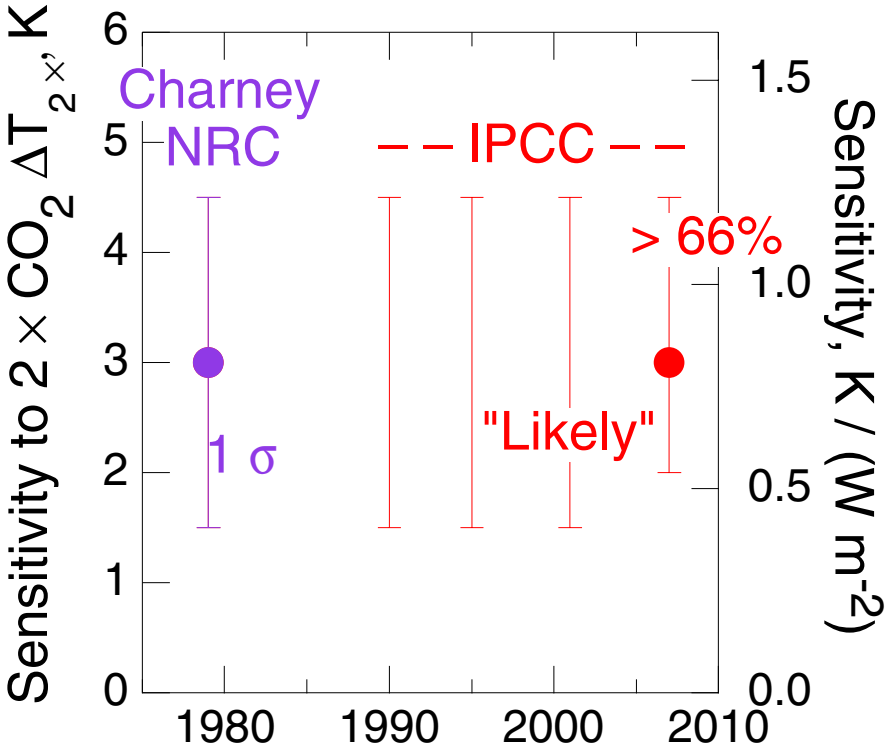
Major national and international assessments

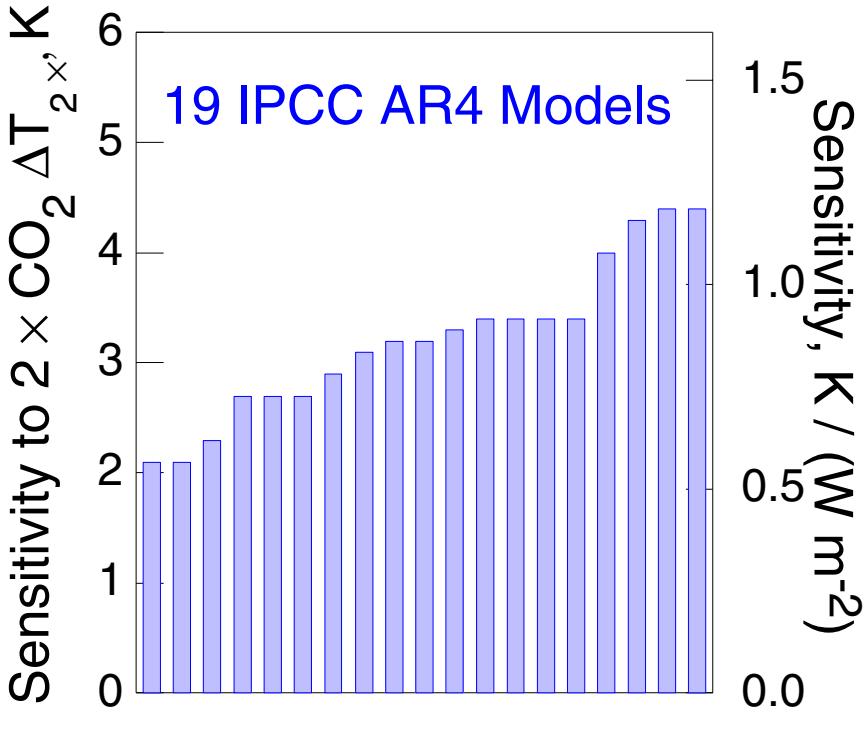


Current estimates of Earth's climate sensitivity are centered about a CO_2 doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty.

ESTIMATES OF EARTH'S CLIMATE SENSITIVITY AND ASSOCIATED UNCERTAINTY

Major national and international assessments and current climate models



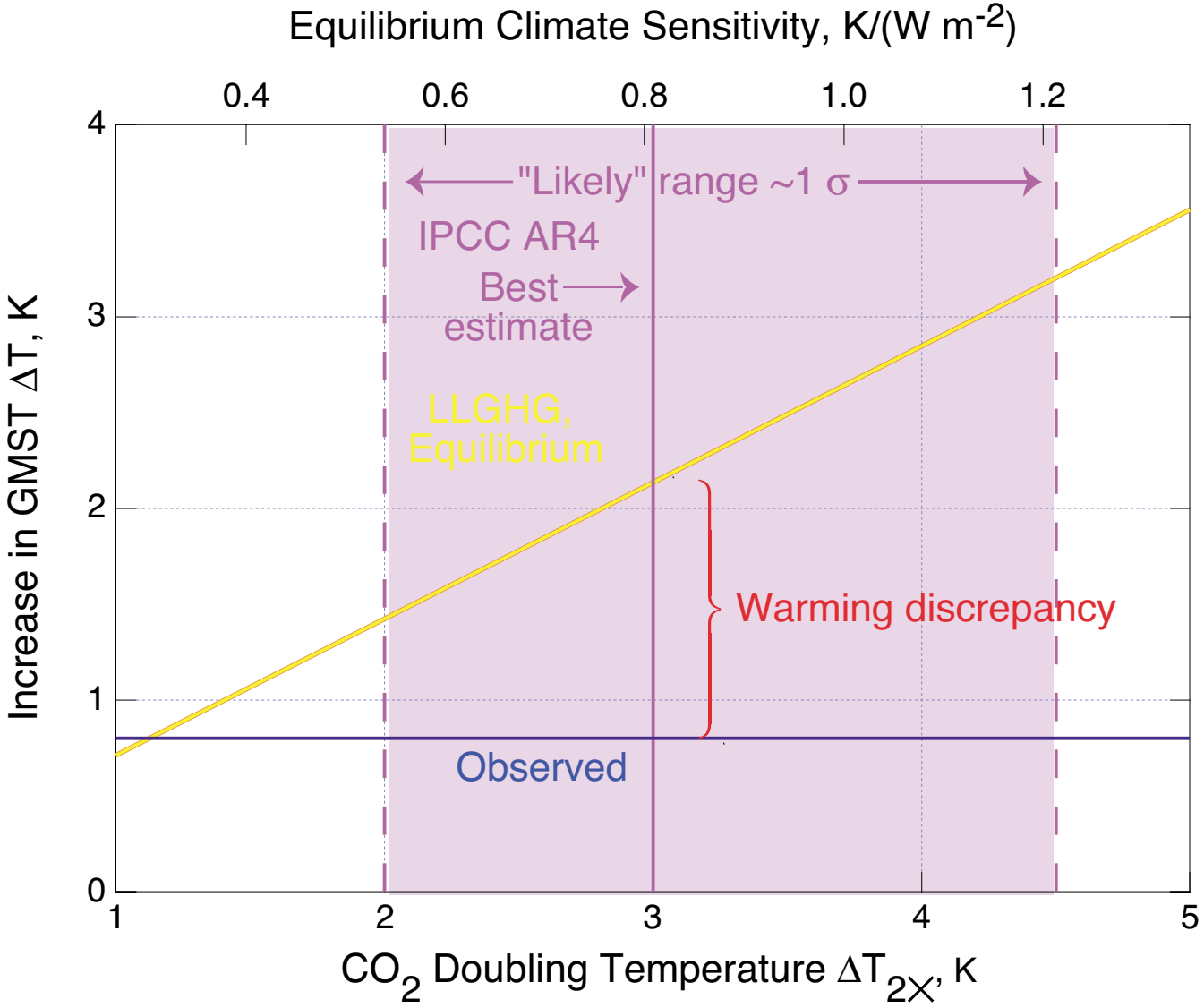


Current estimates of Earth's climate sensitivity are centered about a CO_2 doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty.

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

EXPECTED INCREASE IN GLOBAL TEMPERATURE

Long-lived GHGs only – Dependence on climate sensitivity



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

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From Forcing by Long-lived Greenhouse Gases

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.

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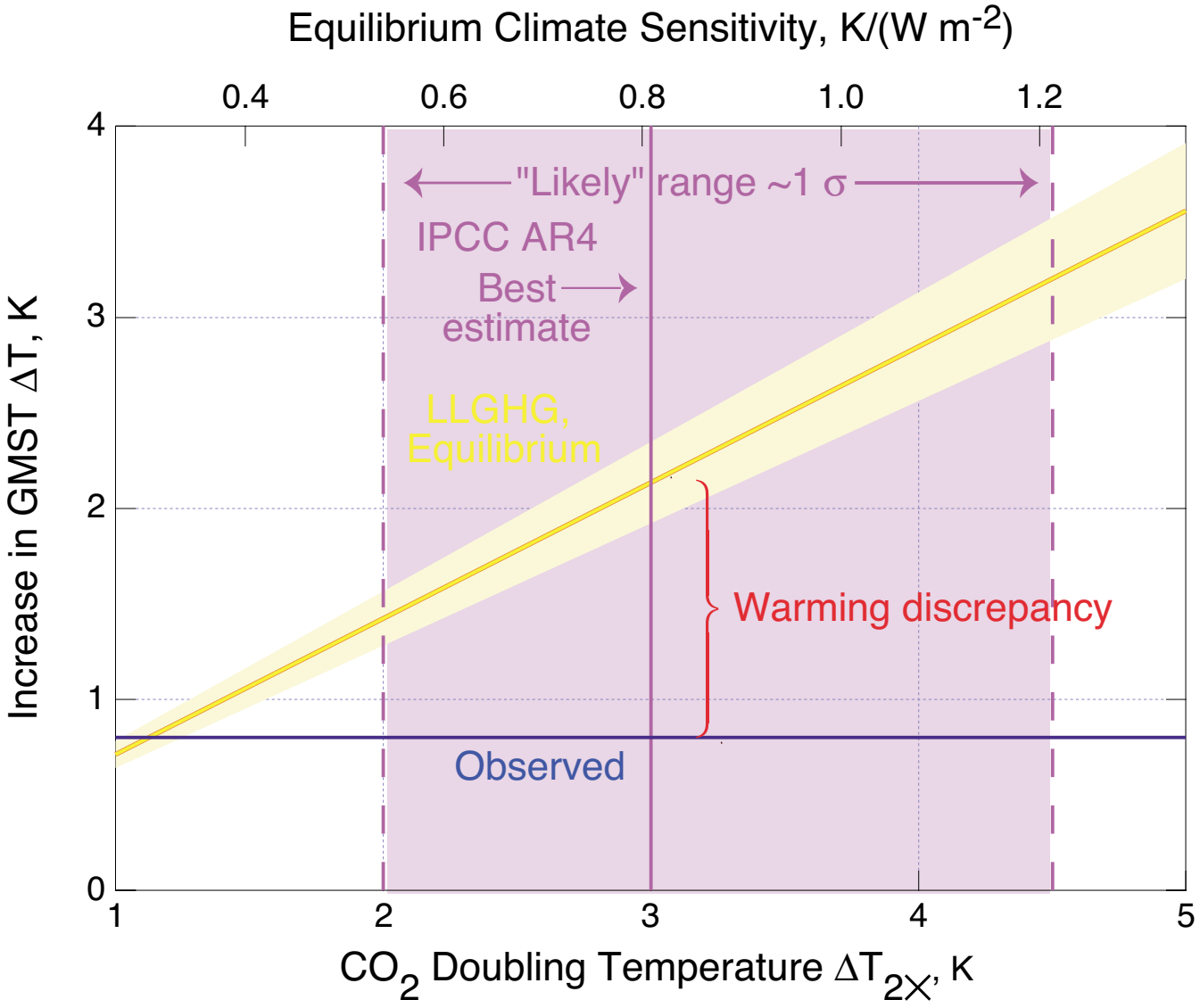

Little of the warming discrepancy is resolved by uncertainty in GHG forcing.

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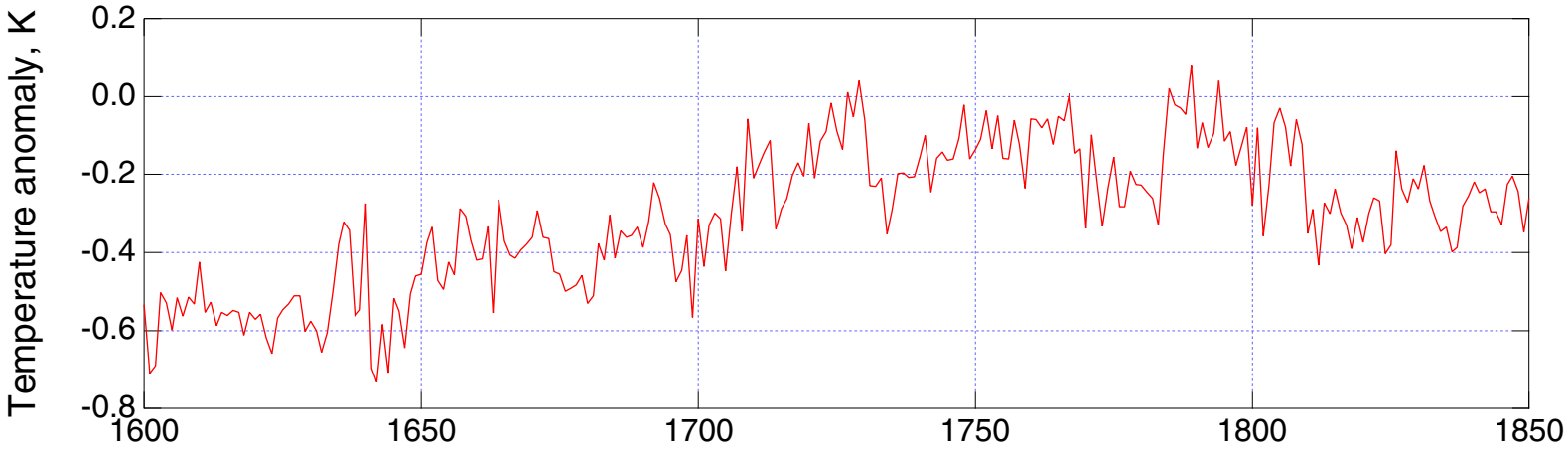
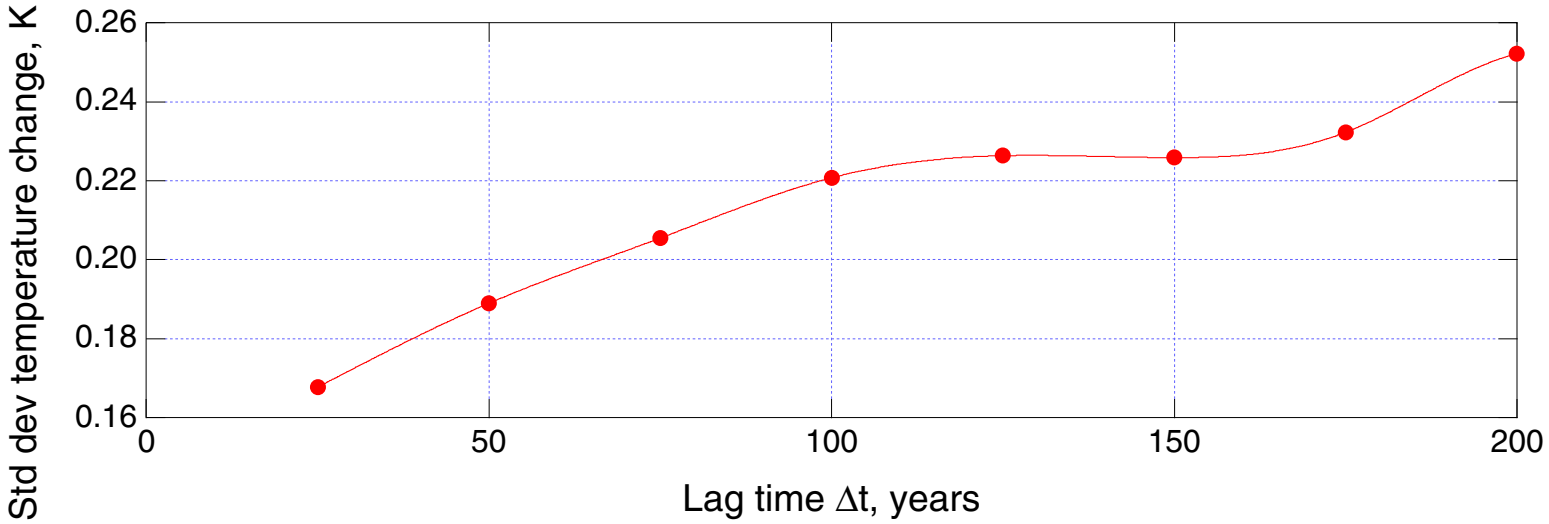
ESTIMATING NATURAL VARIABILITY

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



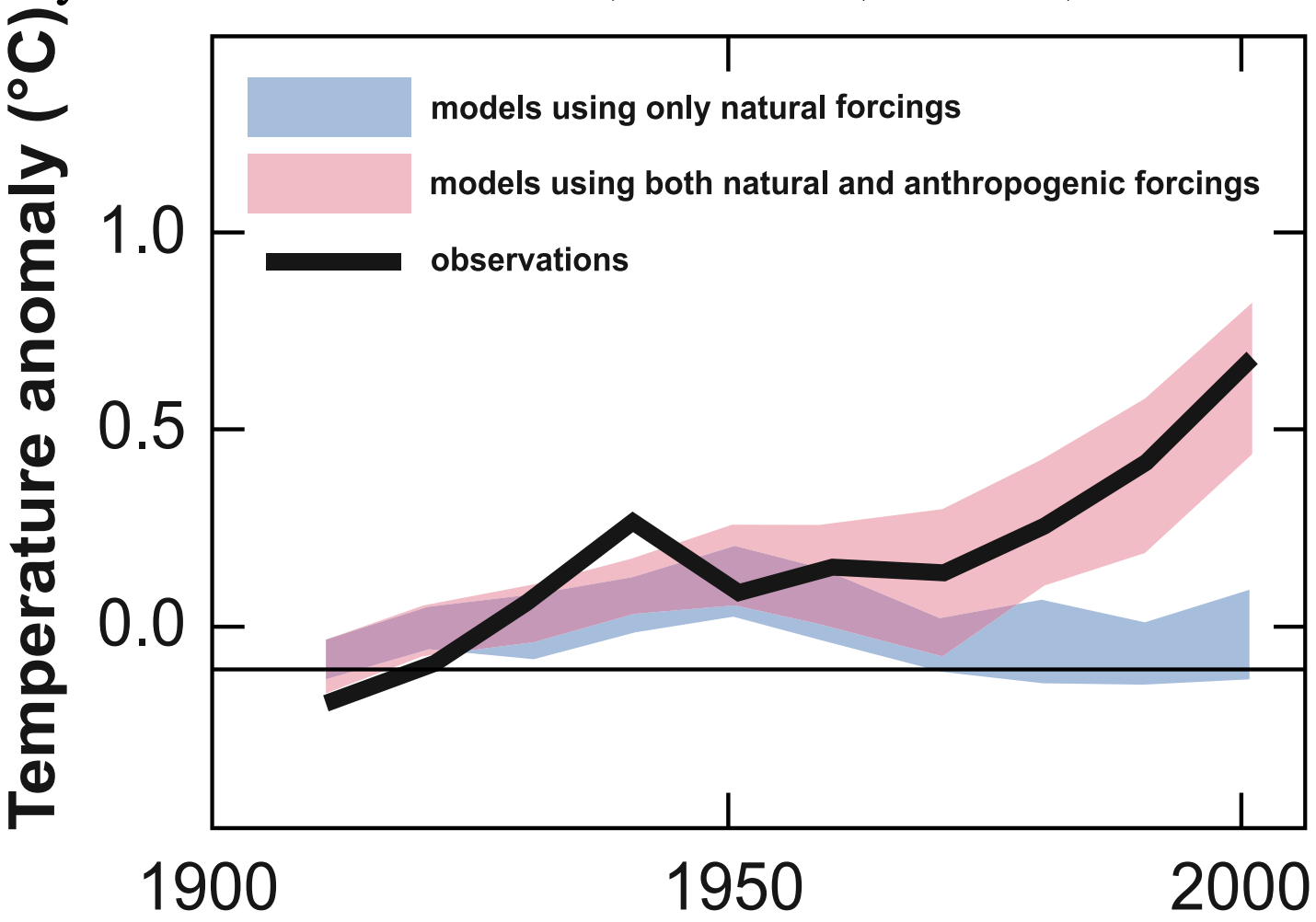
Juckes et al., Climate of the Past, 2007



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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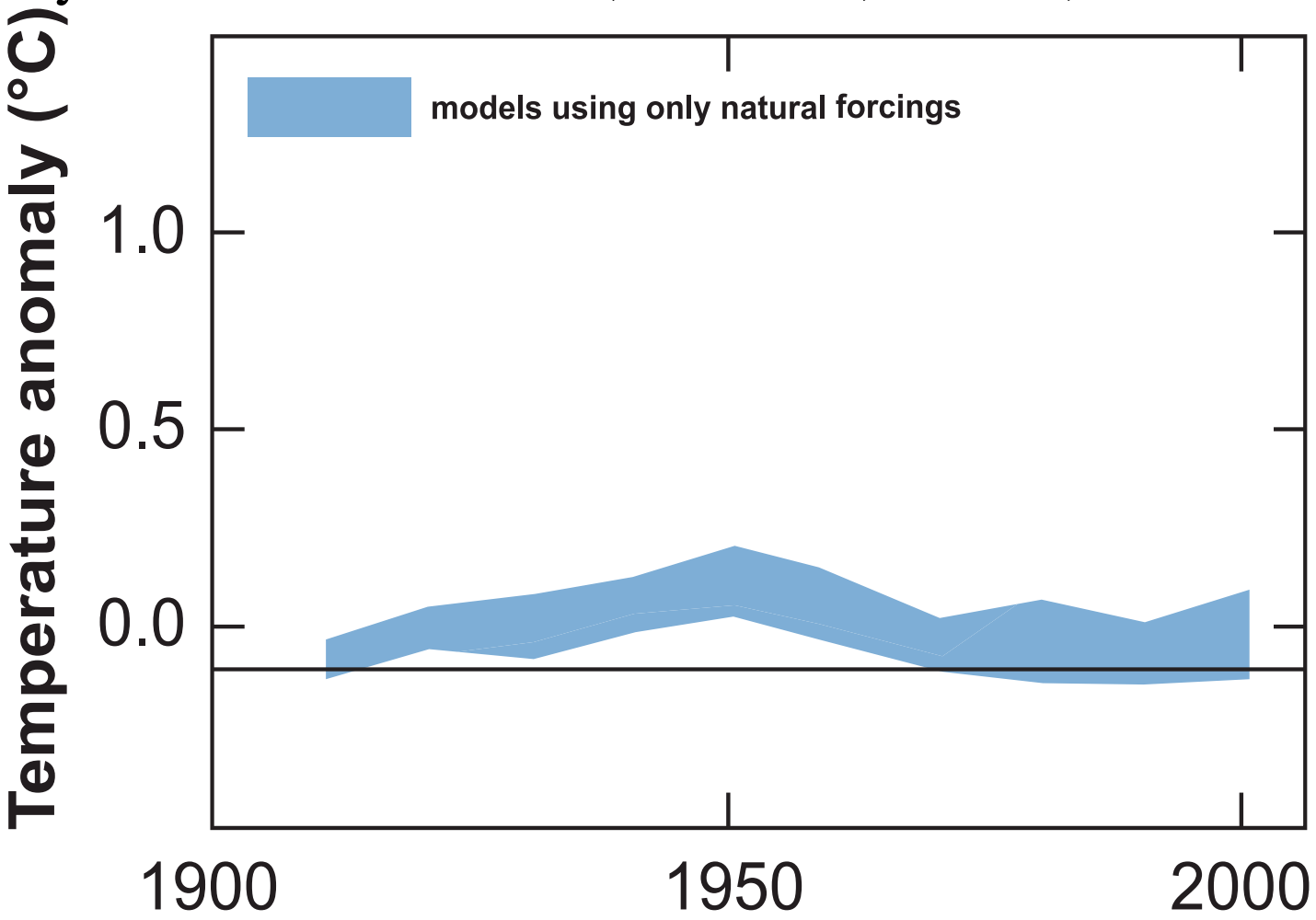

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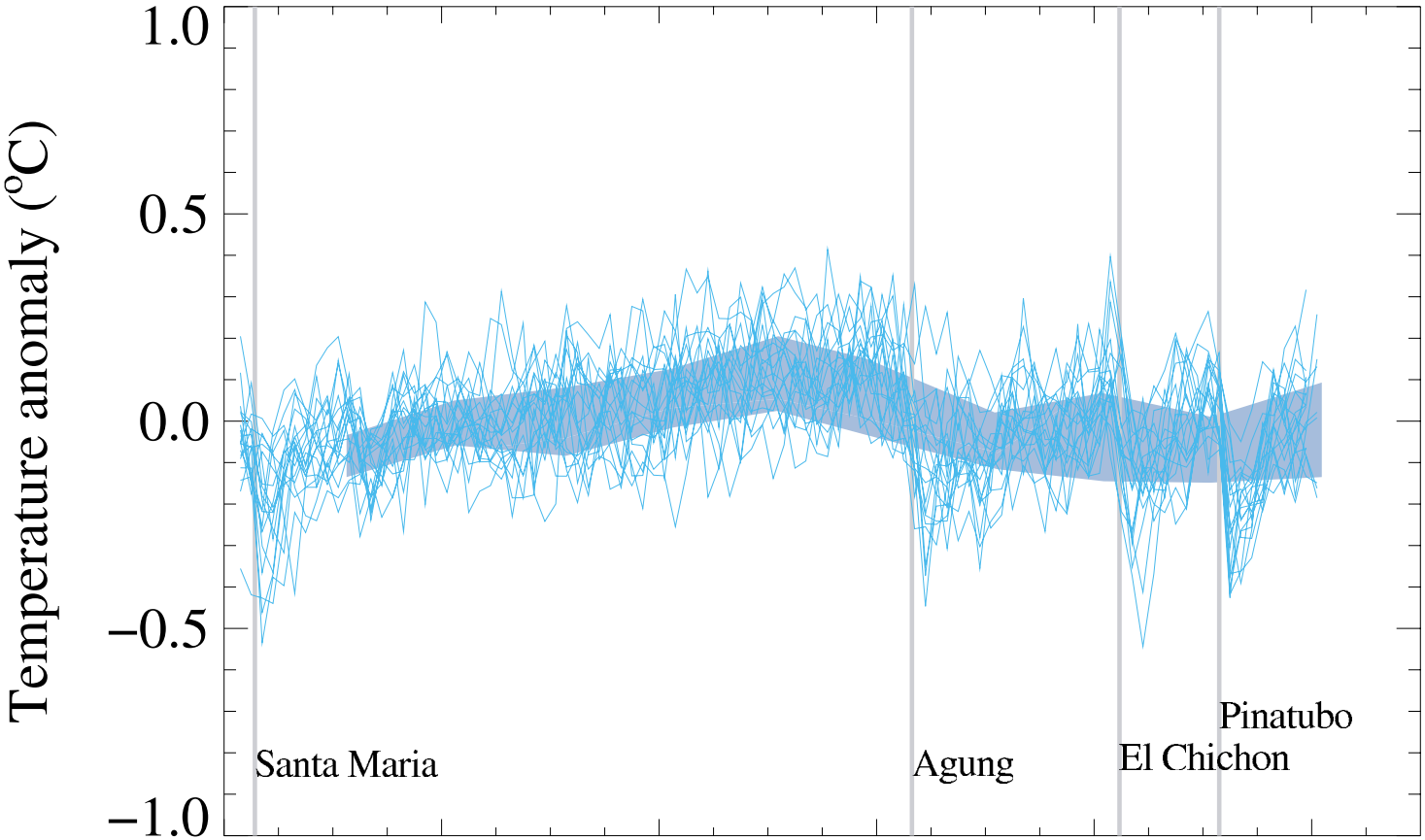
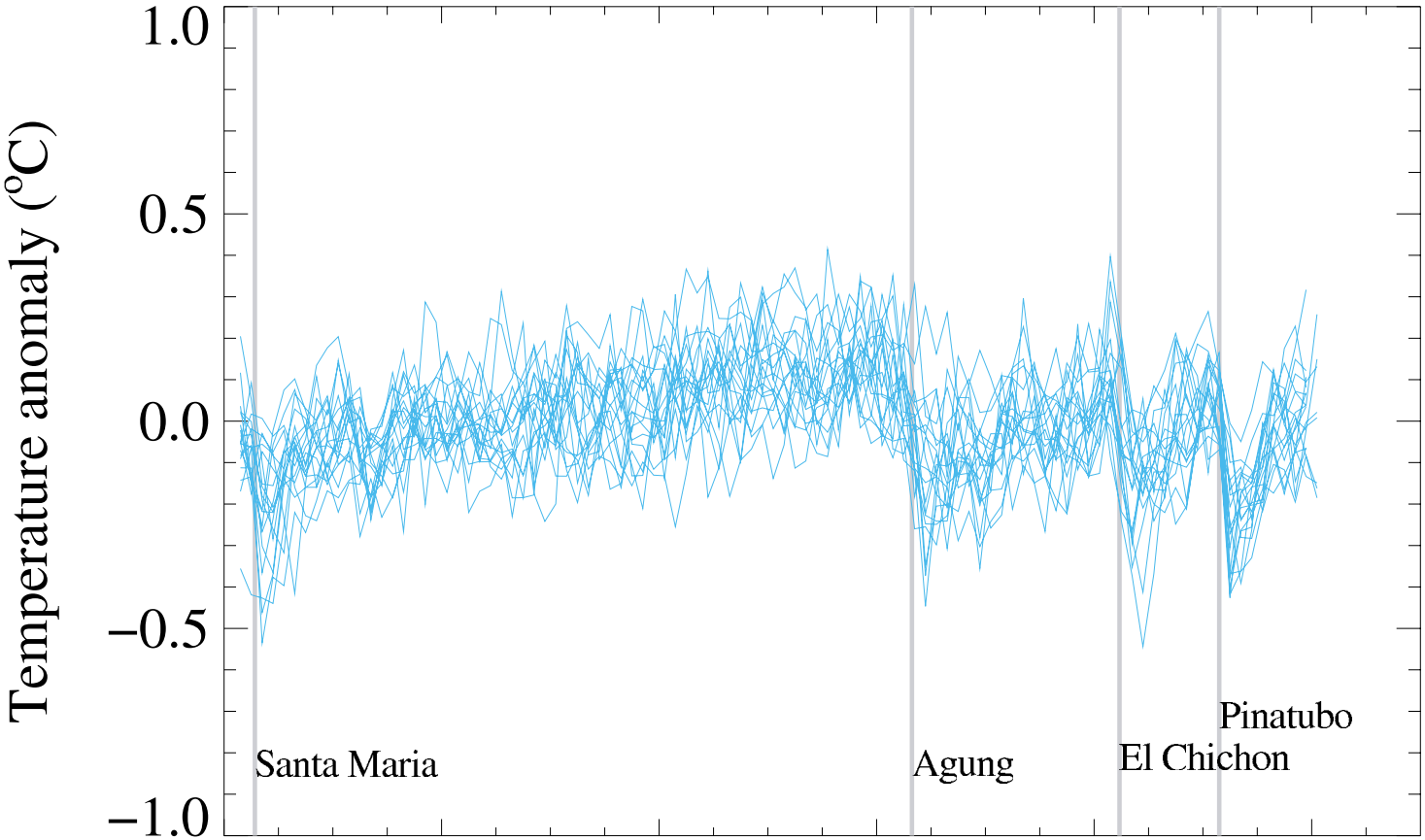


IPCC AR4

ESTIMATING NATURAL VARIABILITY

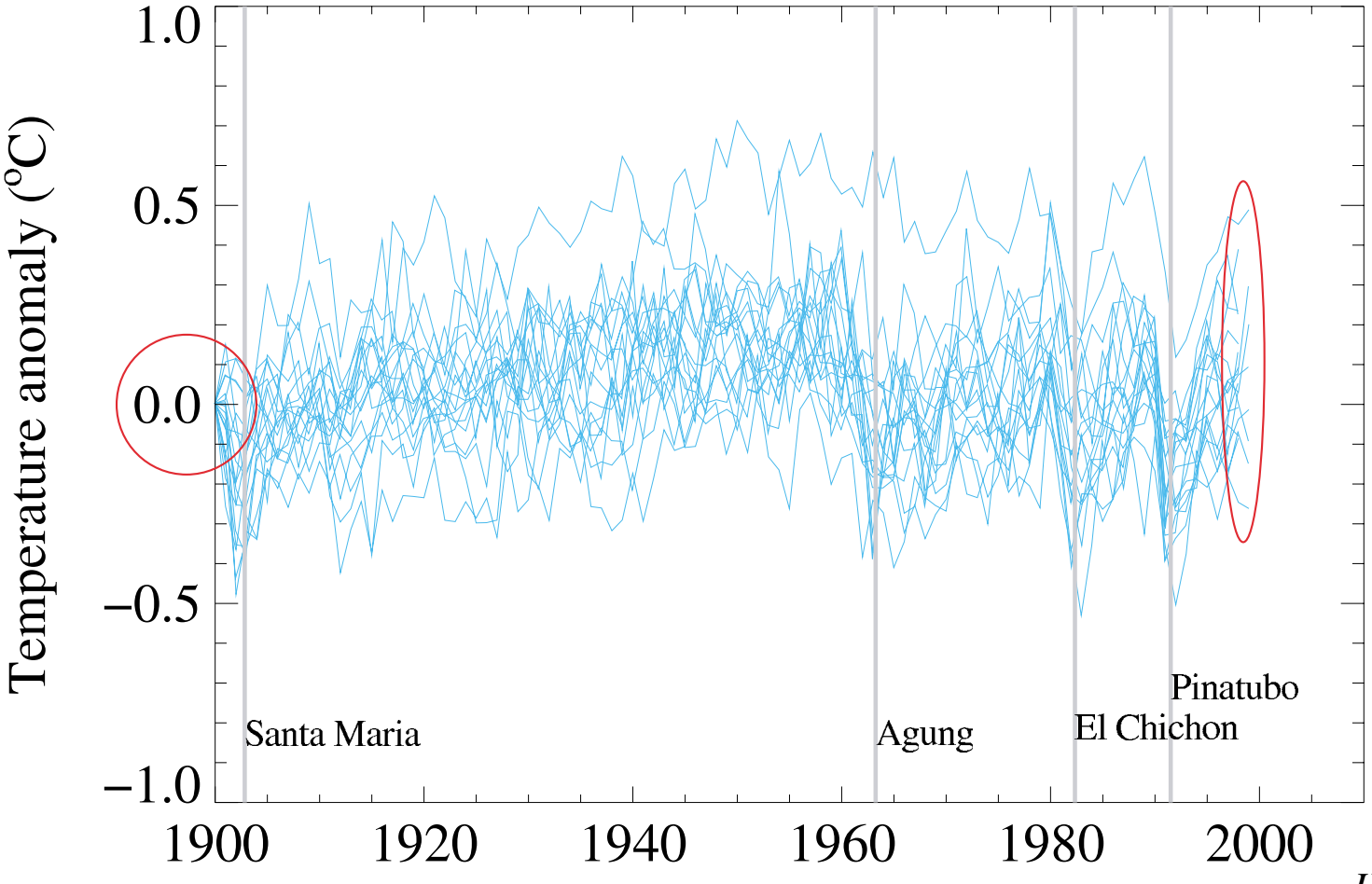
Anomaly relative to 1901-1950; 5 Models, 19 runs, from IPCC AR4



IPCC AR4

ESTIMATING NATURAL VARIABILITY

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

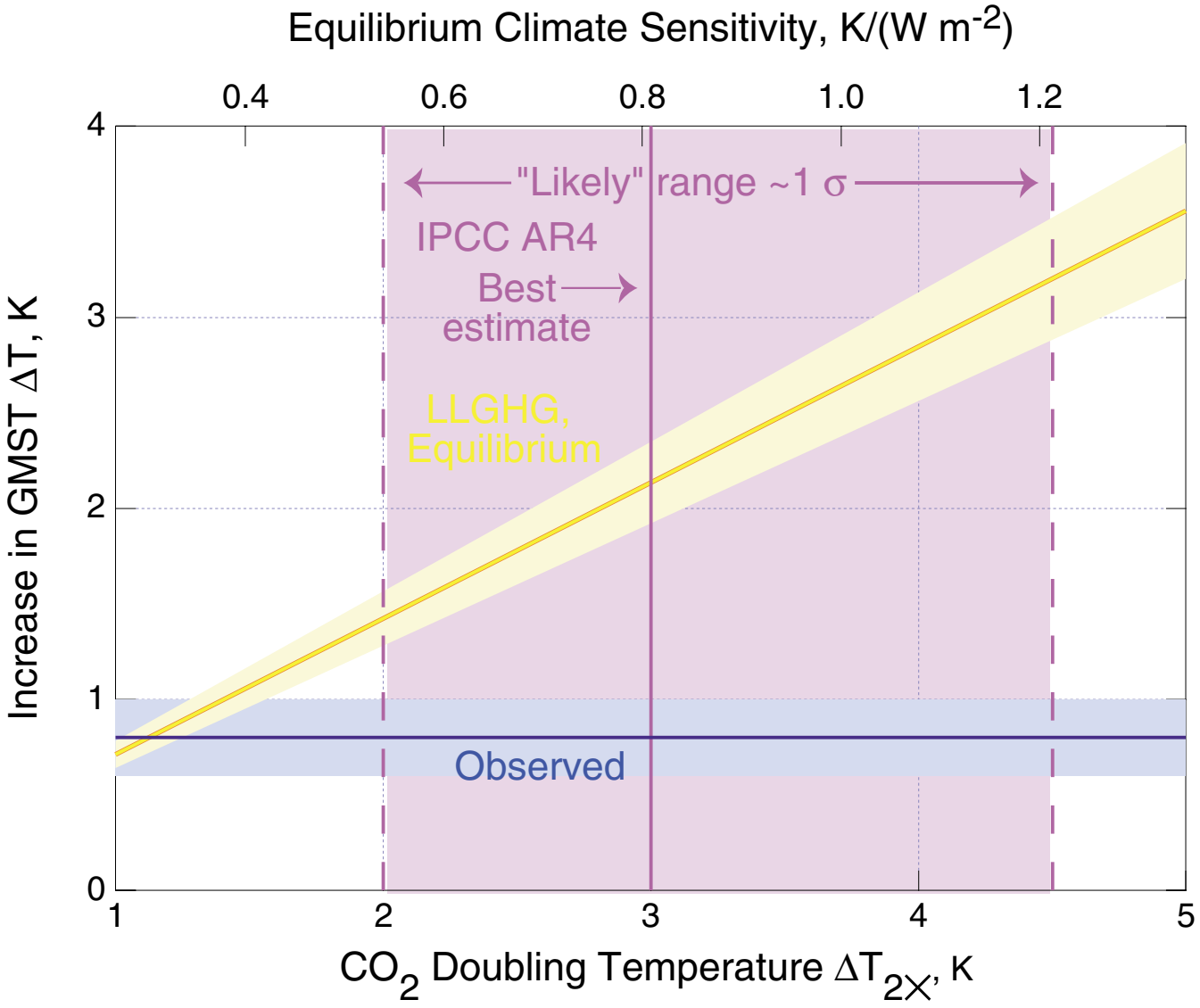


IPCC AR4

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.

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

FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

- Uncertainty in greenhouse gas forcing.
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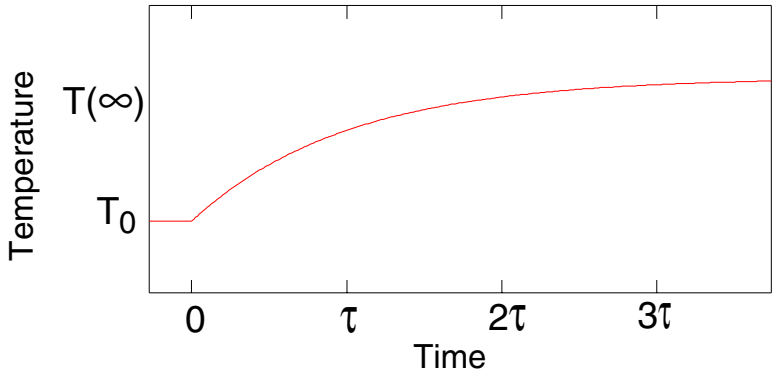
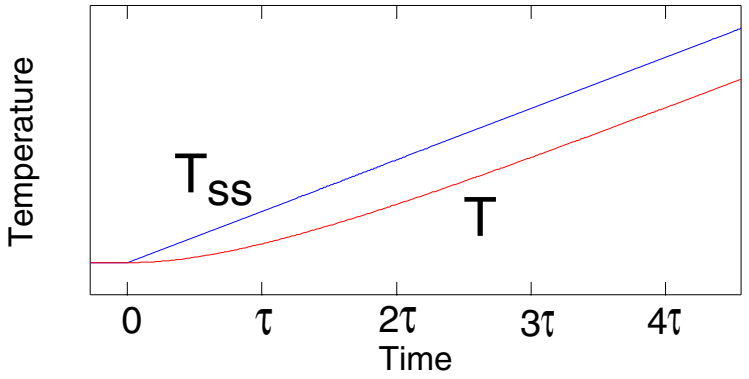
APPROACH TO STEADY STATE

Response to impulse forcing



Response to ramped forcing



τ is the time constant of the system response to a perturbation.

ACCOUNTING FOR DISEQUILIBRIUM

Upon application of a forcing to climate initially at equilibrium

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

$$N = F - S^{-1}\Delta T_s$$

For positive forcing net downwelling radiation at top of atmosphere immediately increases by the amount of the forcing.

As surface temperature T_s increases, outgoing longwave radiation increases and net downwelling radiation decreases until new equilibrium is reached.

EFFECTIVE FORCING

$$N = F - S^{-1}\Delta T_s$$

In general, not at equilibrium,

$$\Delta T_s = S(F - N)$$

Define ***effective forcing***, $F_{\text{eff}} \equiv F - N$

Use of effective forcing permits determination of expected temperature increase ΔT_s as

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

Need to determine net heating rate of Earth, N.

APPROACH TO ACCOUNTING FOR DISEQUILIBRIUM

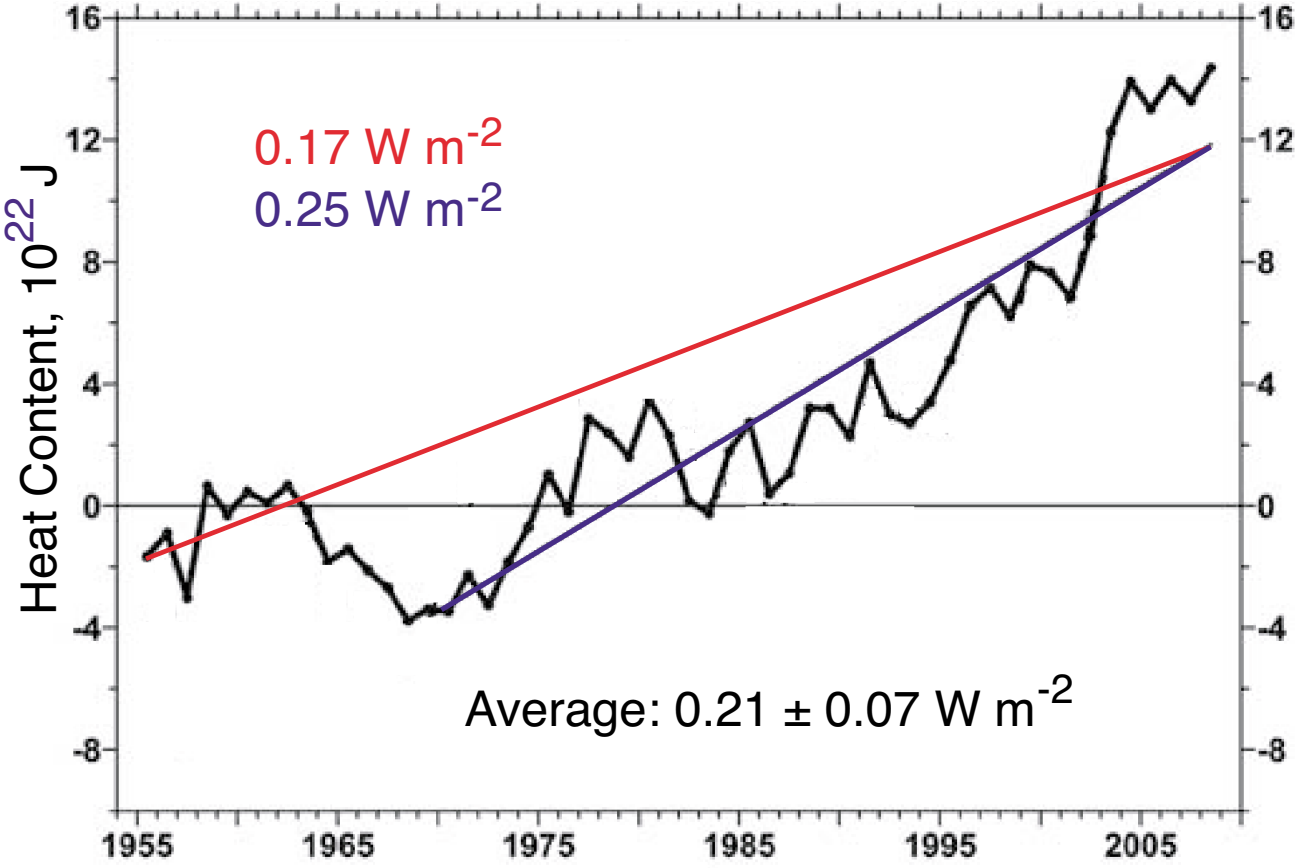
Determine global heating rate from ***increase in heat content of global ocean***.

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

Compare observed ΔT_{s} 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

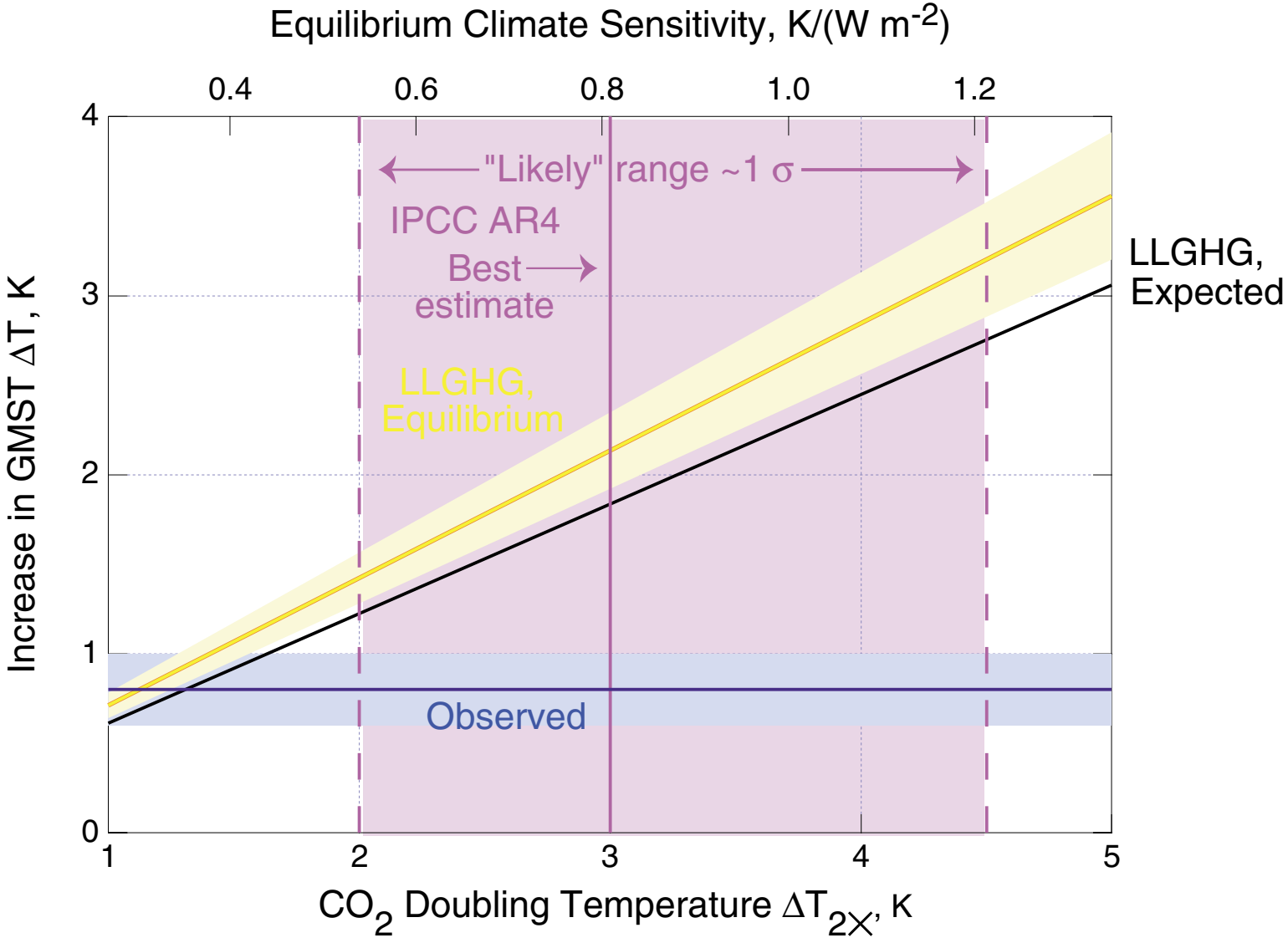
Accounting for heat to 3 km: factor of 1.44.

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

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

EXPECTED INCREASE IN GLOBAL TEMPERATURE

Long-lived GHGs only – Dependence on climate sensitivity



Little of the warming discrepancy can attributed to thermal disequilibrium.

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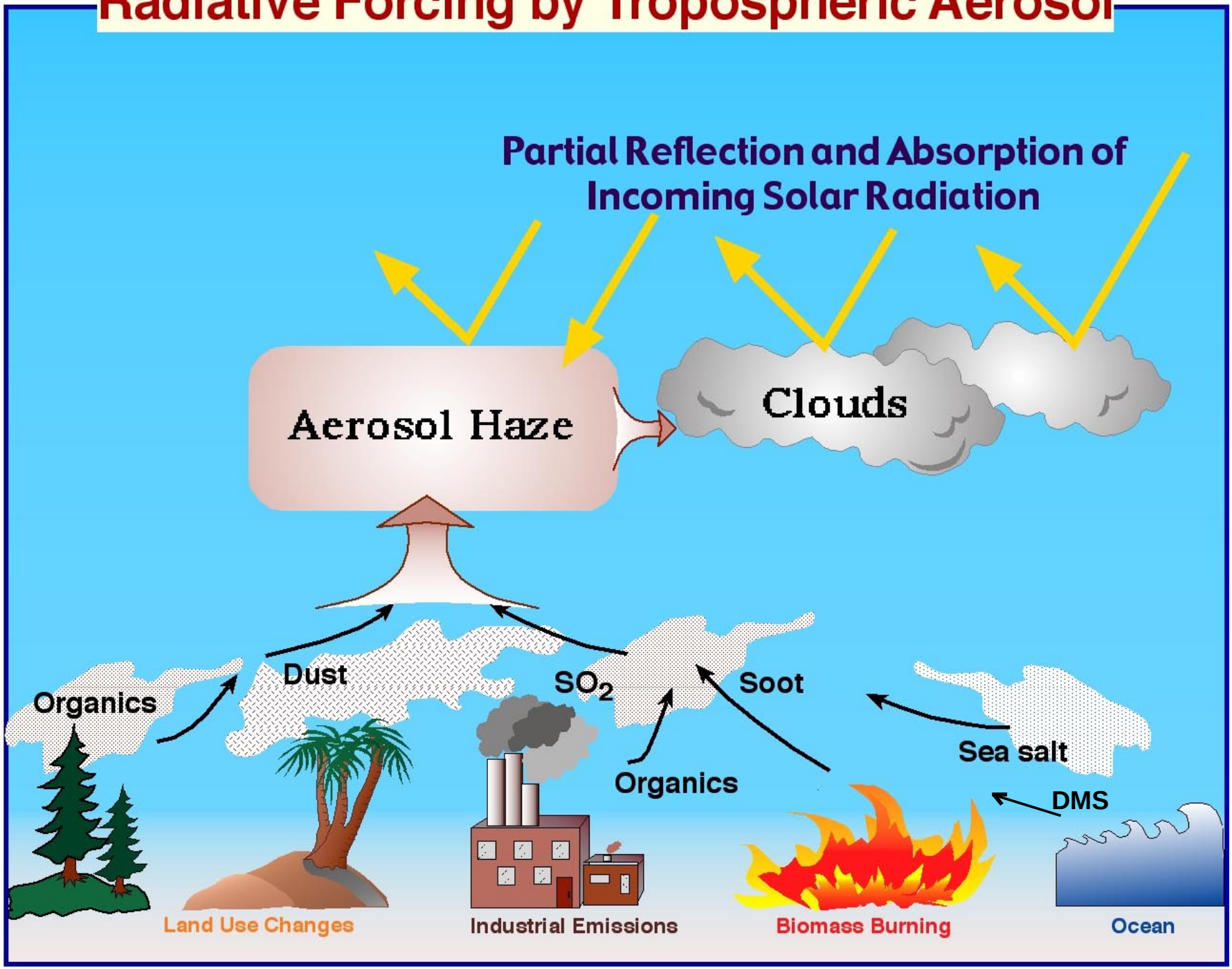
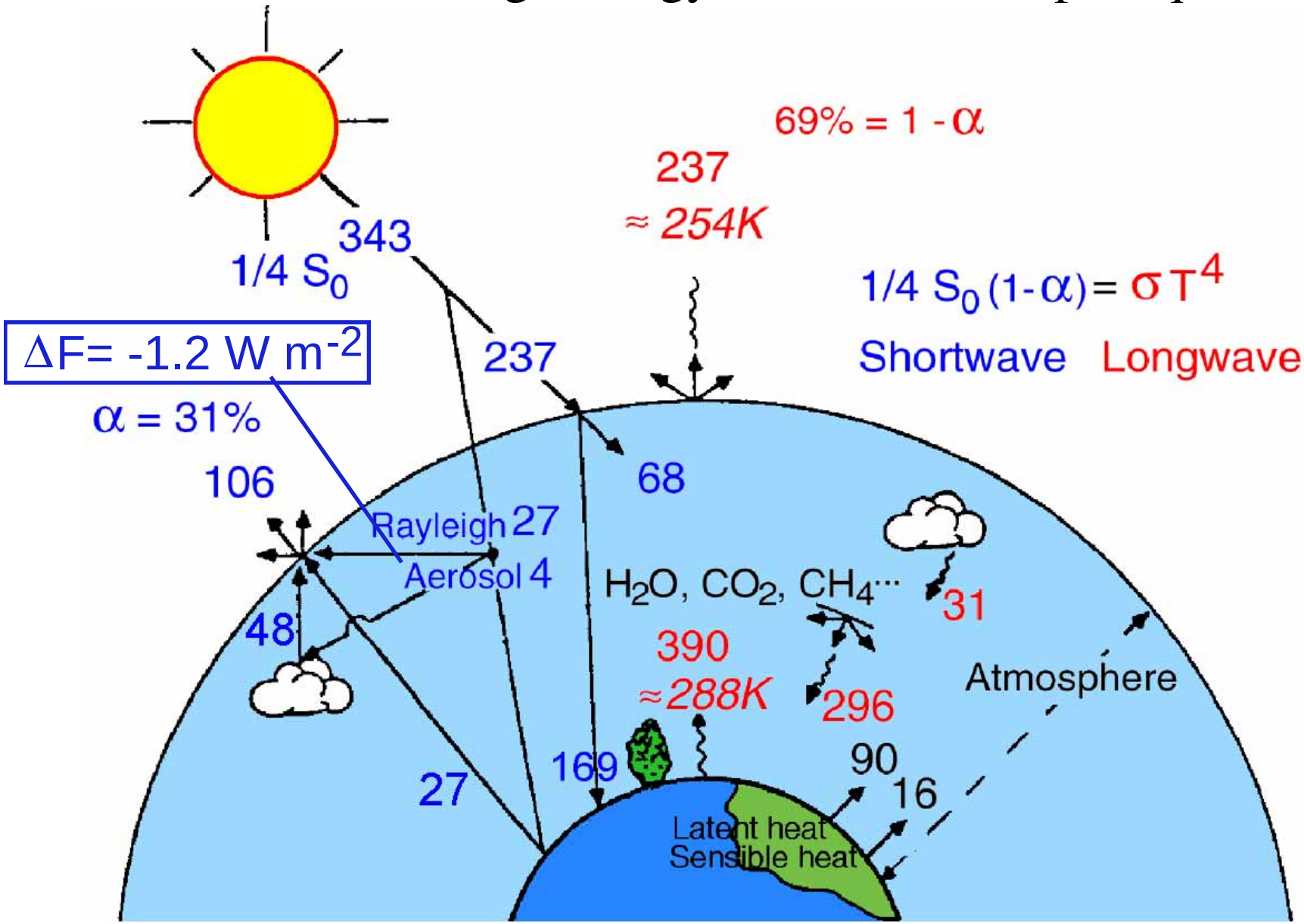
Radiative Forcing by Tropospheric Aerosol



GLOBAL ENERGY BALANCE

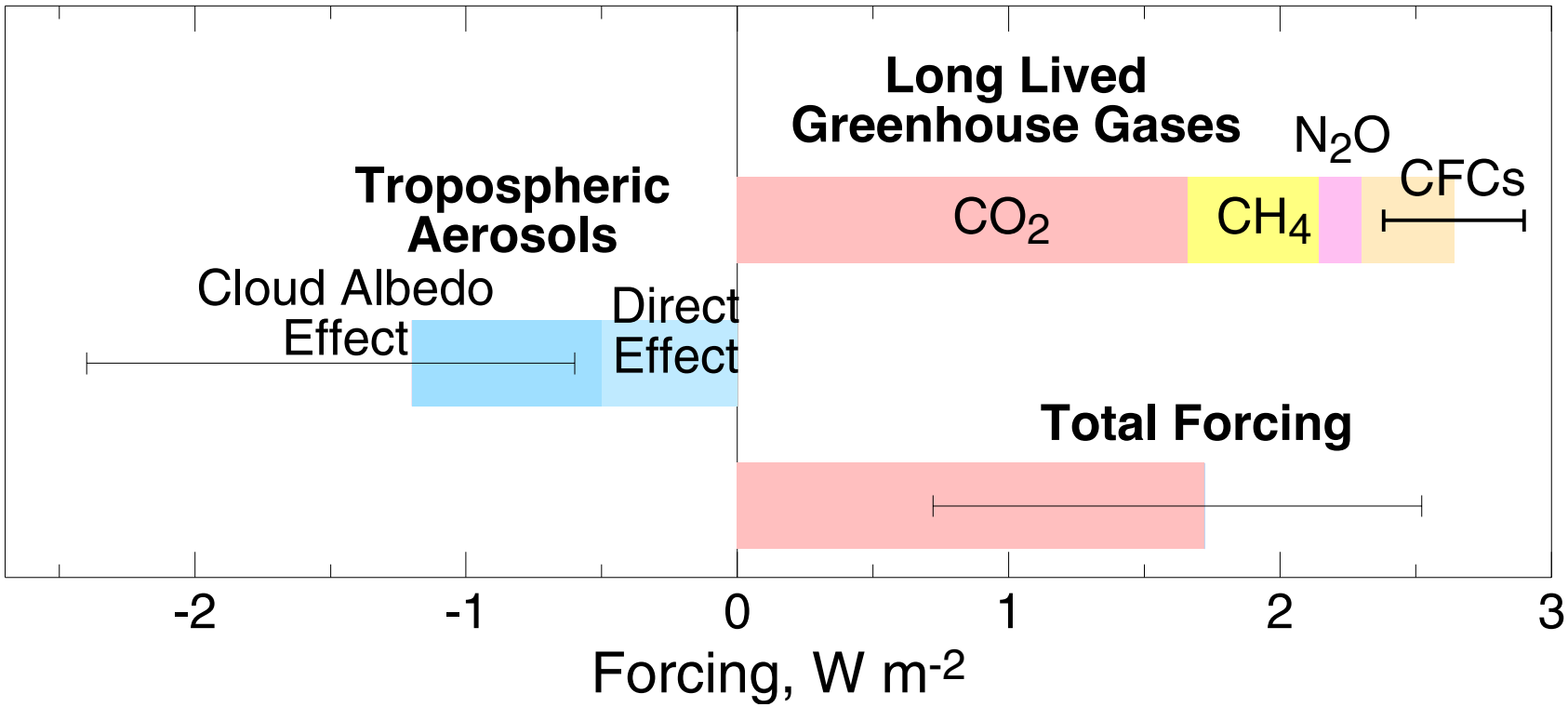
Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)



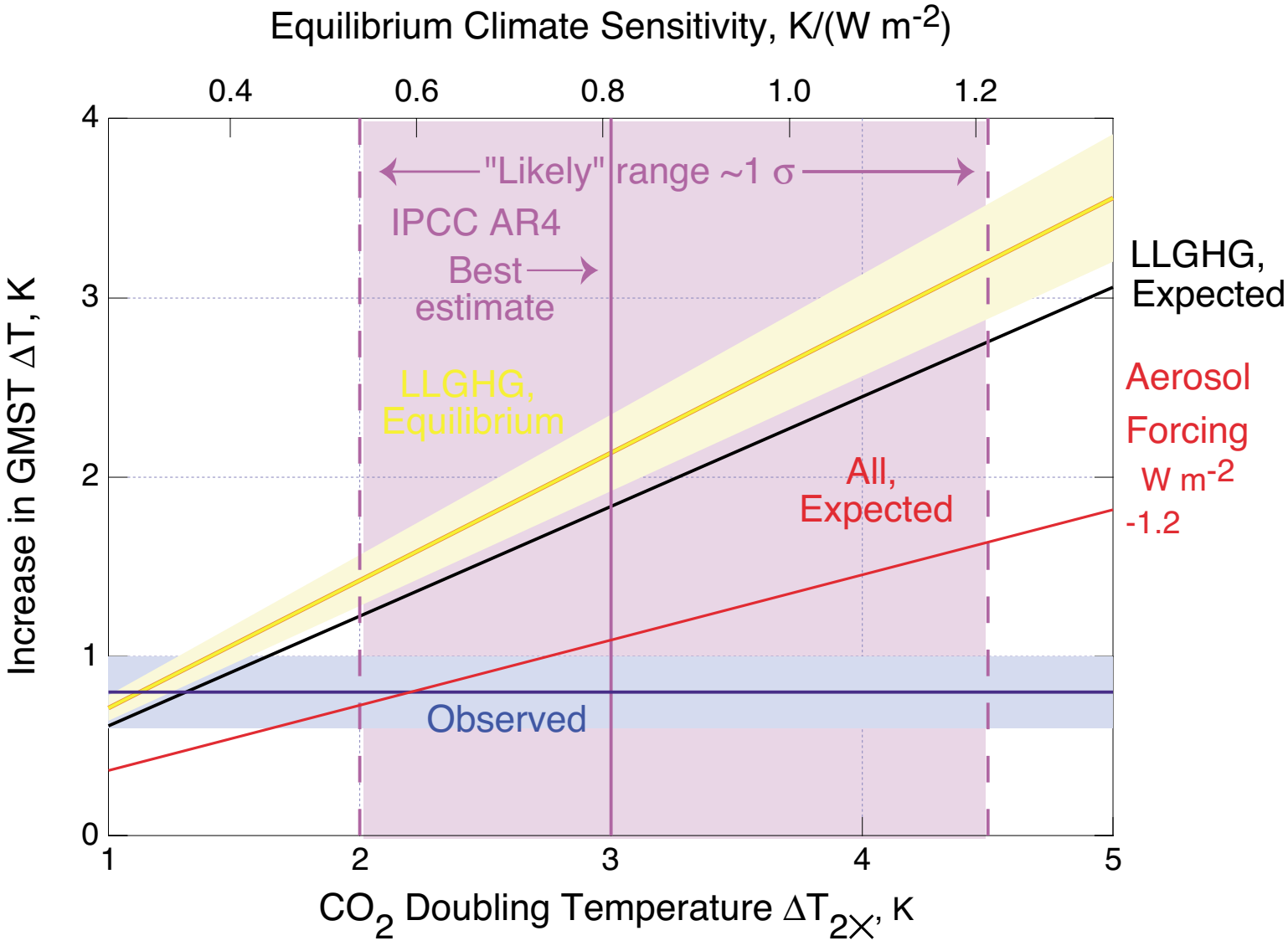
Total forcing includes other anthropogenic and natural (solar) forcings.

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

Uncertainty in aerosol forcing dominates uncertainty in total forcing.

EXPECTED INCREASE IN GLOBAL TEMPERATURE

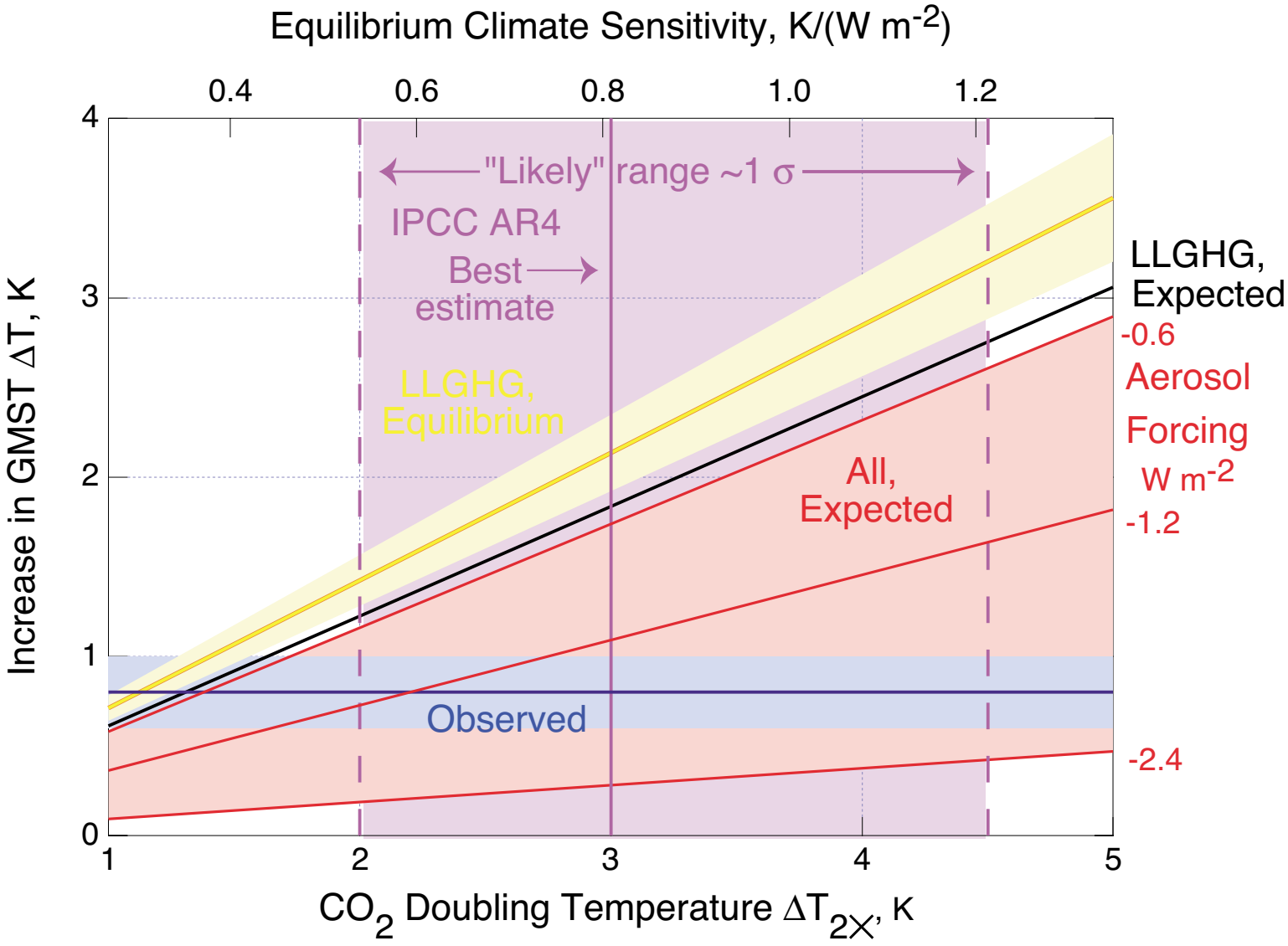
All forcings – Dependence on climate sensitivity



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.

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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.

HOW MUCH WARMING IS EXPECTED?

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:

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

Committed warming

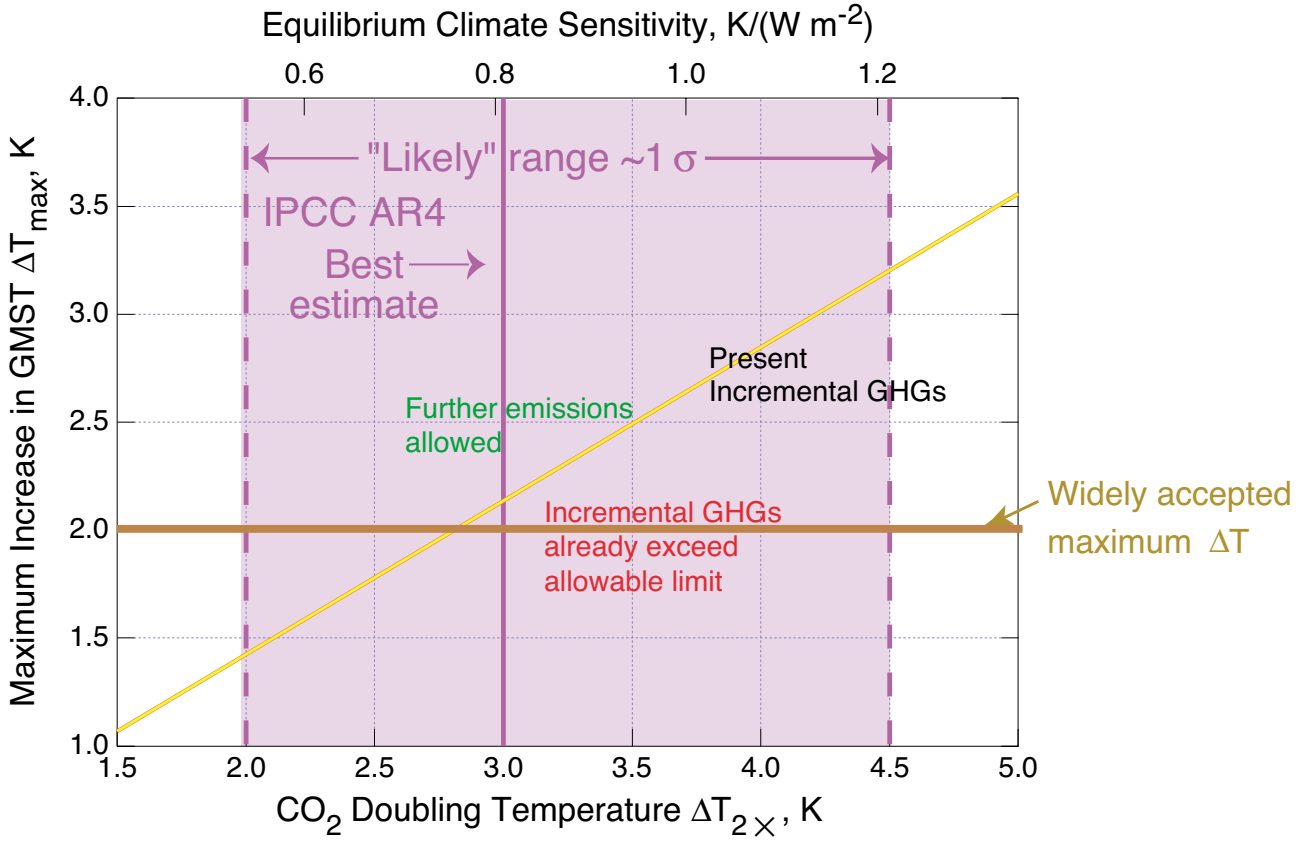
Observed temperature increase:

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

Because of uncertainty in climate sensitivity the committed warming is likewise uncertain.

ALLOWABLE FUTURE CO_2 EMISSIONS

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

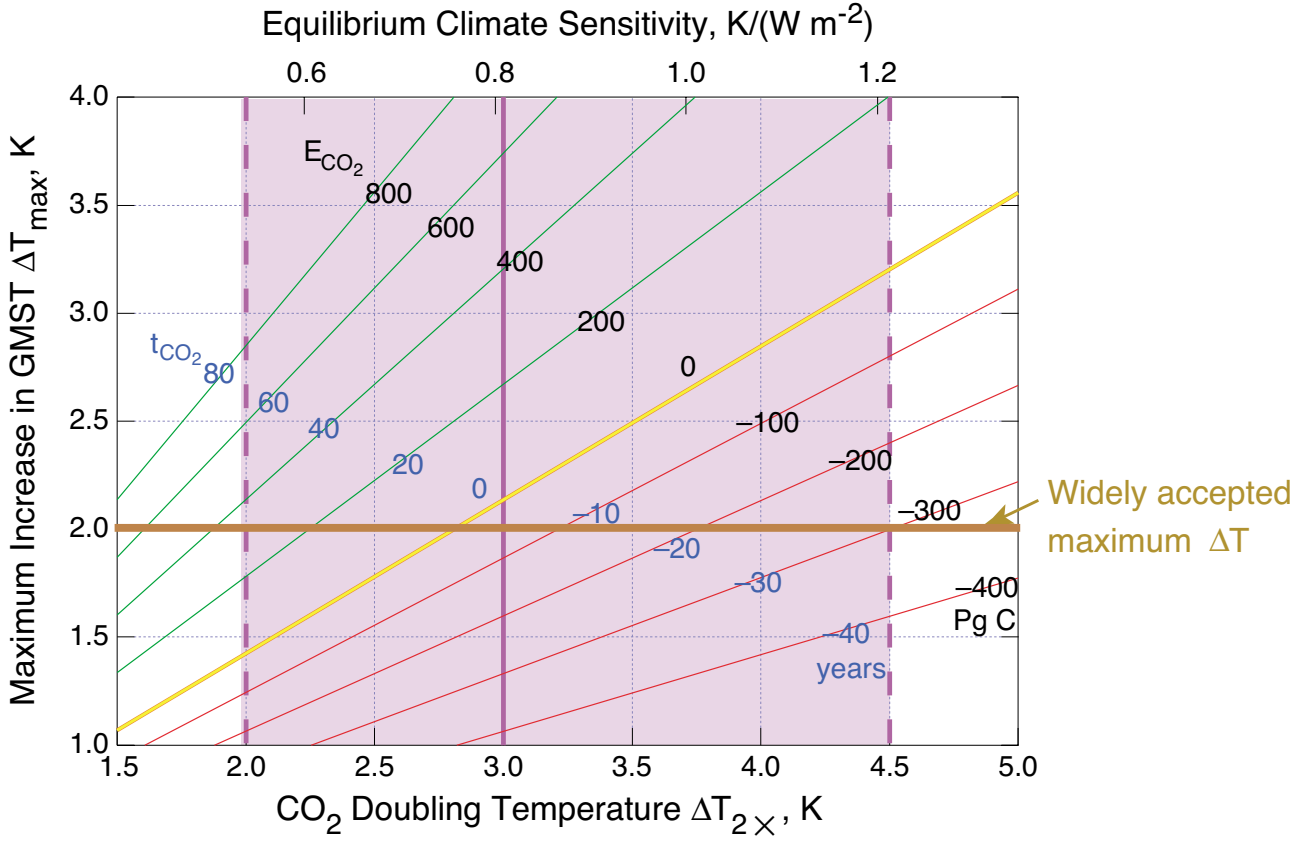


If $\Delta T_{\max} > 2.1$ K and/or sensitivity $\Delta T_{2\times} < 3$ K, further emissions are allowed without exceeding $\Delta T_{\max}$.

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

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

APPROACHES TO DETERMINING CLIMATE SENSITIVITY

Climate models

Evaluate by performance on current climate

Evaluate by performance over instrumental record

Empirical

$Sensitivity = Time\ constant/Heat\ Capacity$

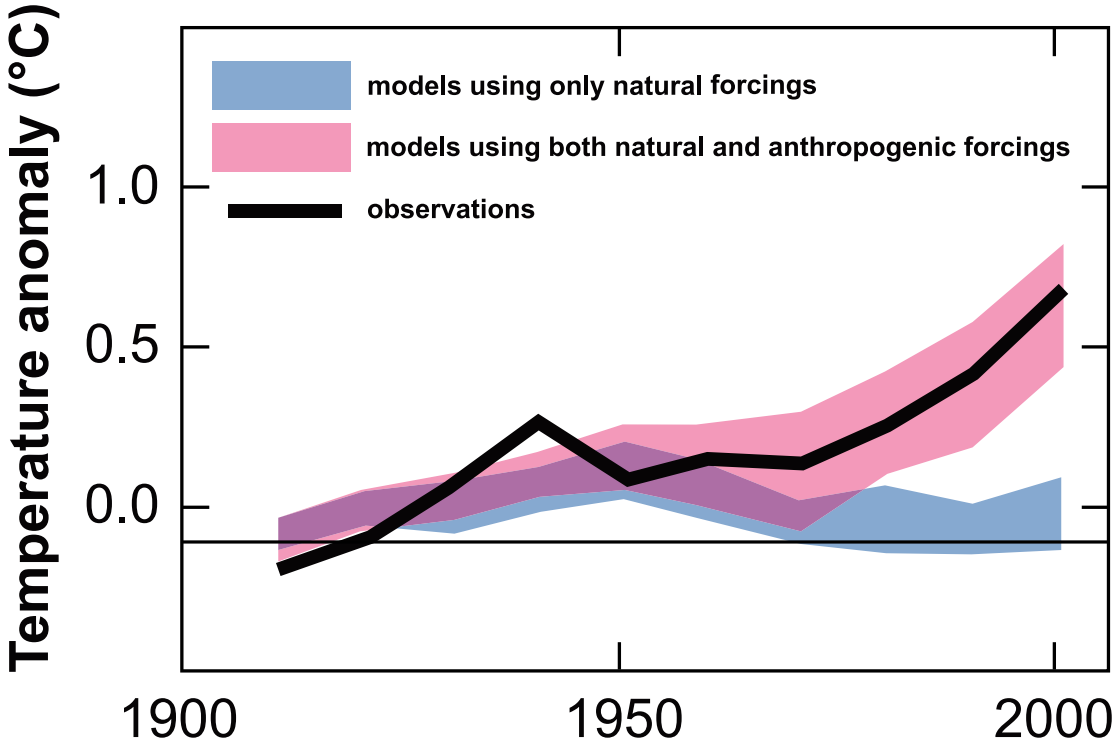
Paleo: $\Delta Temperature/\Delta Flux$, paleo to present

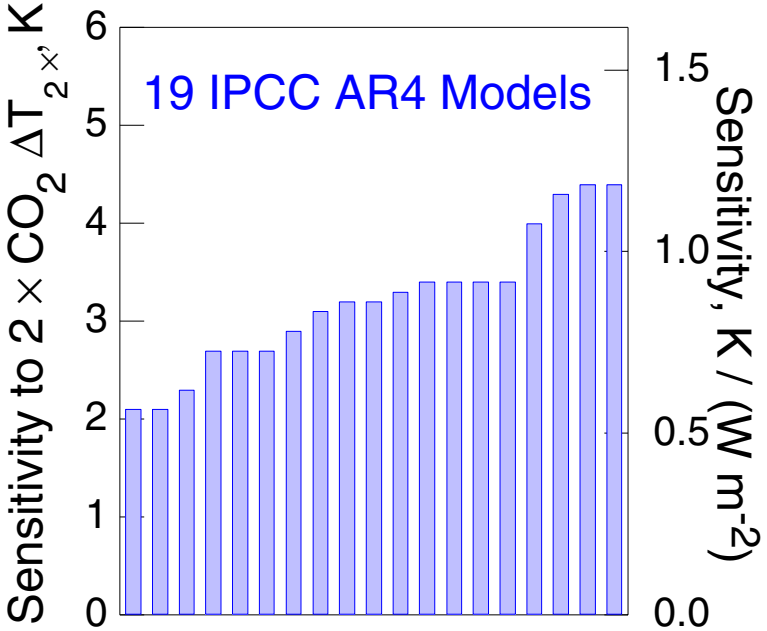
Instrumental record $\Delta Temperature/(Forcing - Flux)$

Satellite measmt.: $[d(Forcing - Flux)/dTemperature]^{-1}$

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

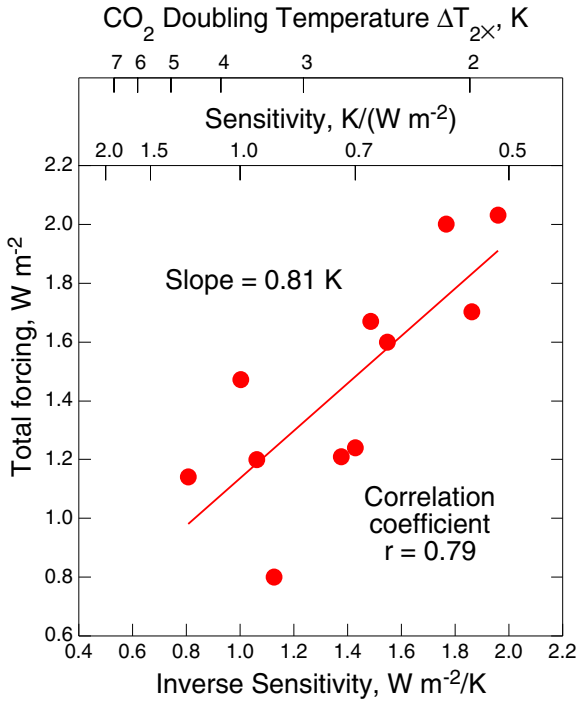
How can this be?

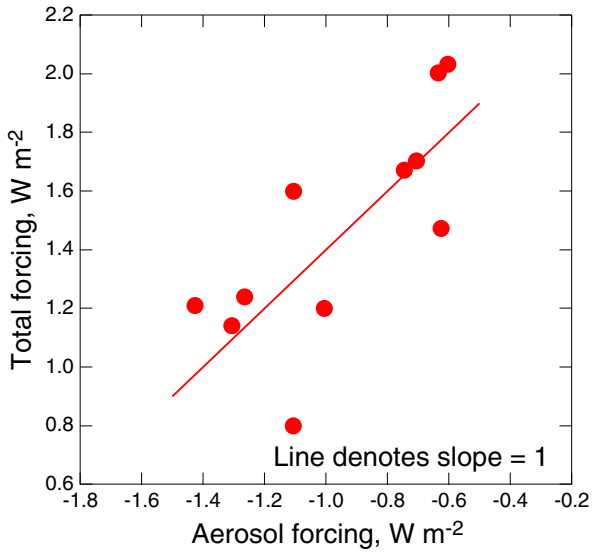
CORRELATION OF AEROSOL FORCING, TOTAL FORCING, AND SENSITIVITY IN CLIMATE MODELS

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.

APPROACHES TO DETERMINING CLIMATE SENSITIVITY

Climate models

Evaluate by performance on current climate

Evaluate by performance over instrumental record

Empirical

Sensitivity = Time constant/Heat Capacity

Paleo: $\Delta Temperature/\Delta Flux$, paleo to present

Instrumental record $\Delta Temperature/(Forcing - Flux)$

Satellite measmt.: $[d(Forcing - Flux)/dTemperature]^{-1}$

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

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

.

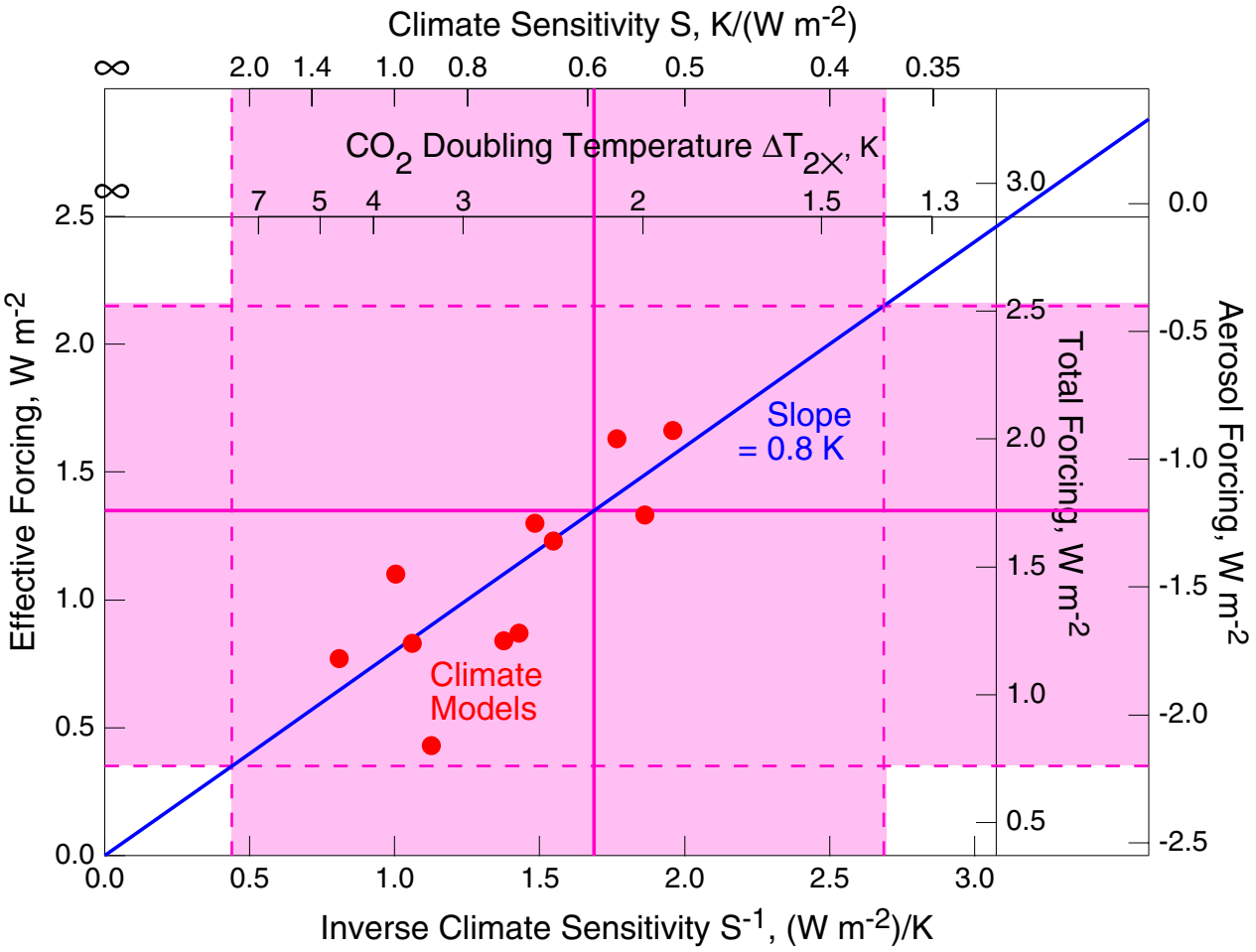
CLIMATE MODEL DETERMINATION OF CLIMATE SENSITIVITY

Effect of uncertainty in forcing

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

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

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



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.

cont'd

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***.