EARTH'S CLIMATE SENSITIVITY: APPARENT INCONSISTENCIES IN RECENT ANALYSES

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Climate Sensitivity

The “Holy Grail” of Climate Research

EQUILIBRIUM CLIMATE SENSITIVITY ECS

The expected steady-state increase in global mean surface temperature ΔT_s in response to sustained forcing F is:

$$\Delta T_s(\infty) = S_{eq} F$$

S_{eq} is "equilibrium" sensitivity of Earth's climate system, $\mathrm{K}/(\mathrm{W\ m^{-2}})$.

Equilibrium climate sensitivity ECS (steady-state response to sustained $2 \times CO_2$ forcing) $\quad \mathrm{ECS}\ [\mathrm{K}/(3.7\ \mathrm{W\ m^{-2}})] \equiv S_{eq} \times (3.7\ \mathrm{W\ m^{-2}})$

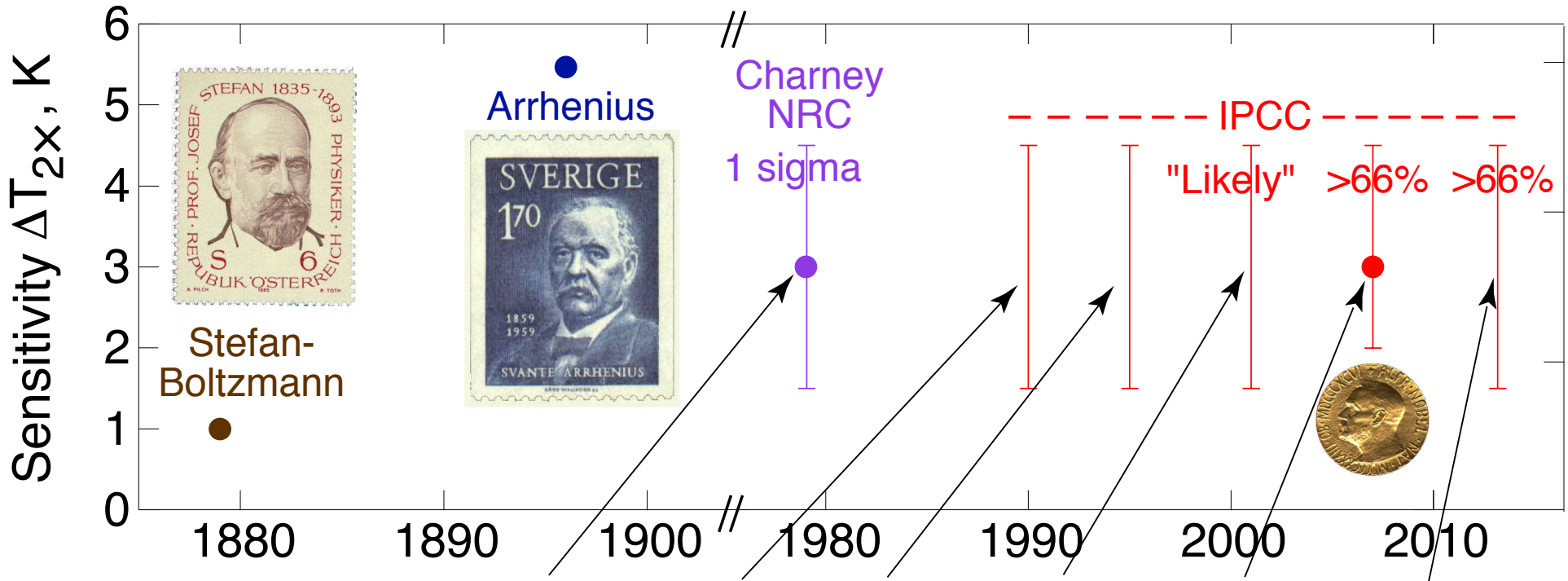
Synonyms: Equilibrium sensitivity, Climate sensitivity, Sensitivity, Doubling temperature $\Delta T_{2\times}$, all in units °C or K.

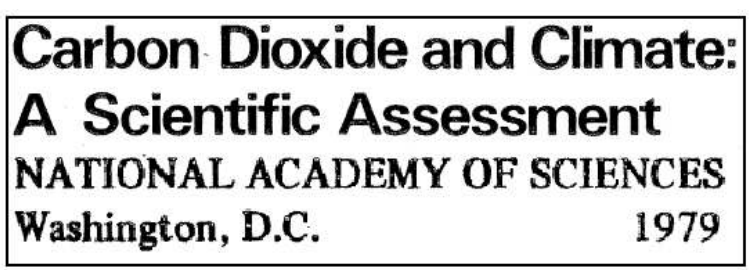
$$\mathrm{ECS} \overset{?}{=} 3\ \mathrm{K}/(3.7\ \mathrm{W\ m^{-2}})$$

It is essential to know the ***climate sensitivity*** and the ***forcing*** to interpret past change in Earth's temperature and to project future changes.

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

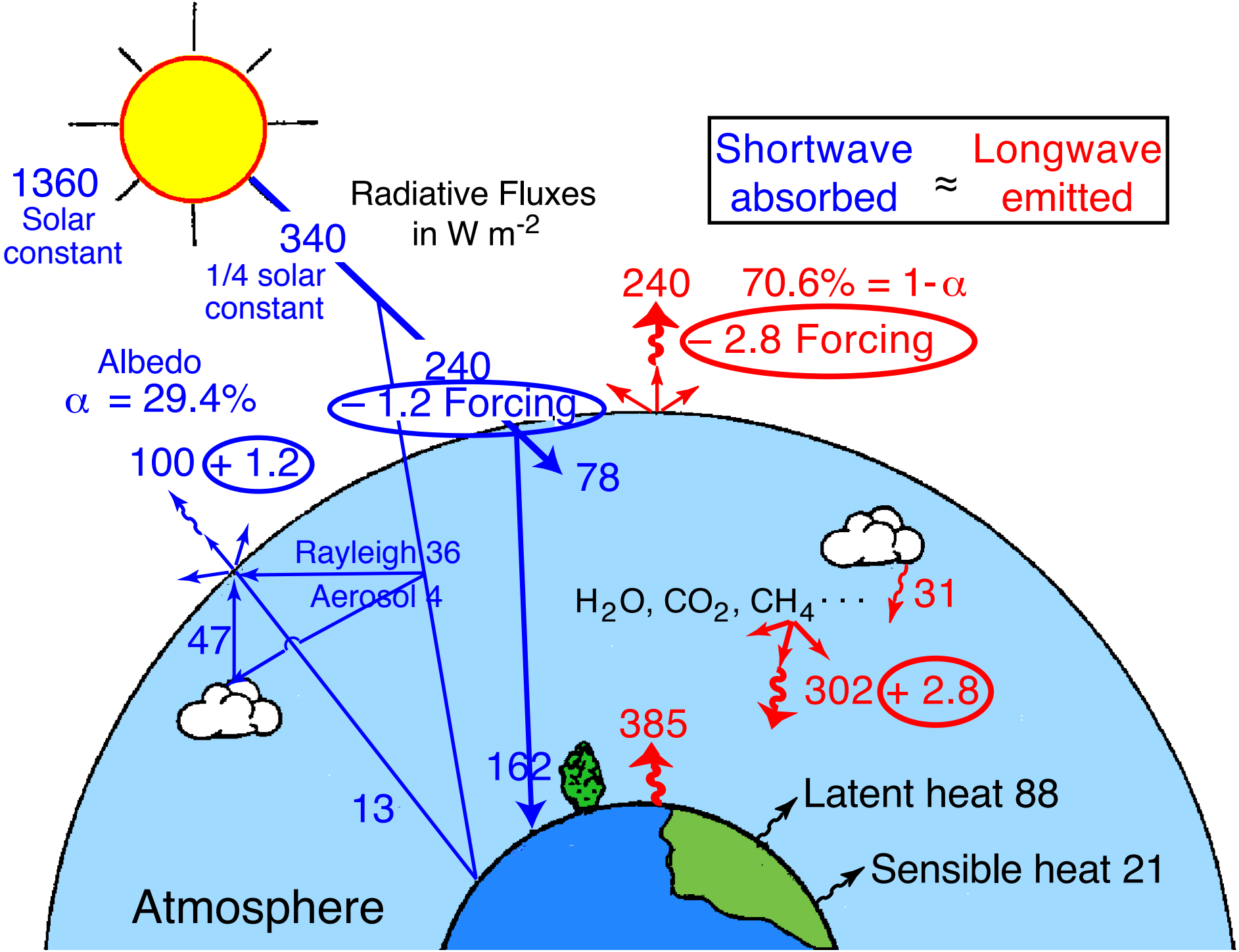
Estimates of central value and uncertainty range from major national and international assessments





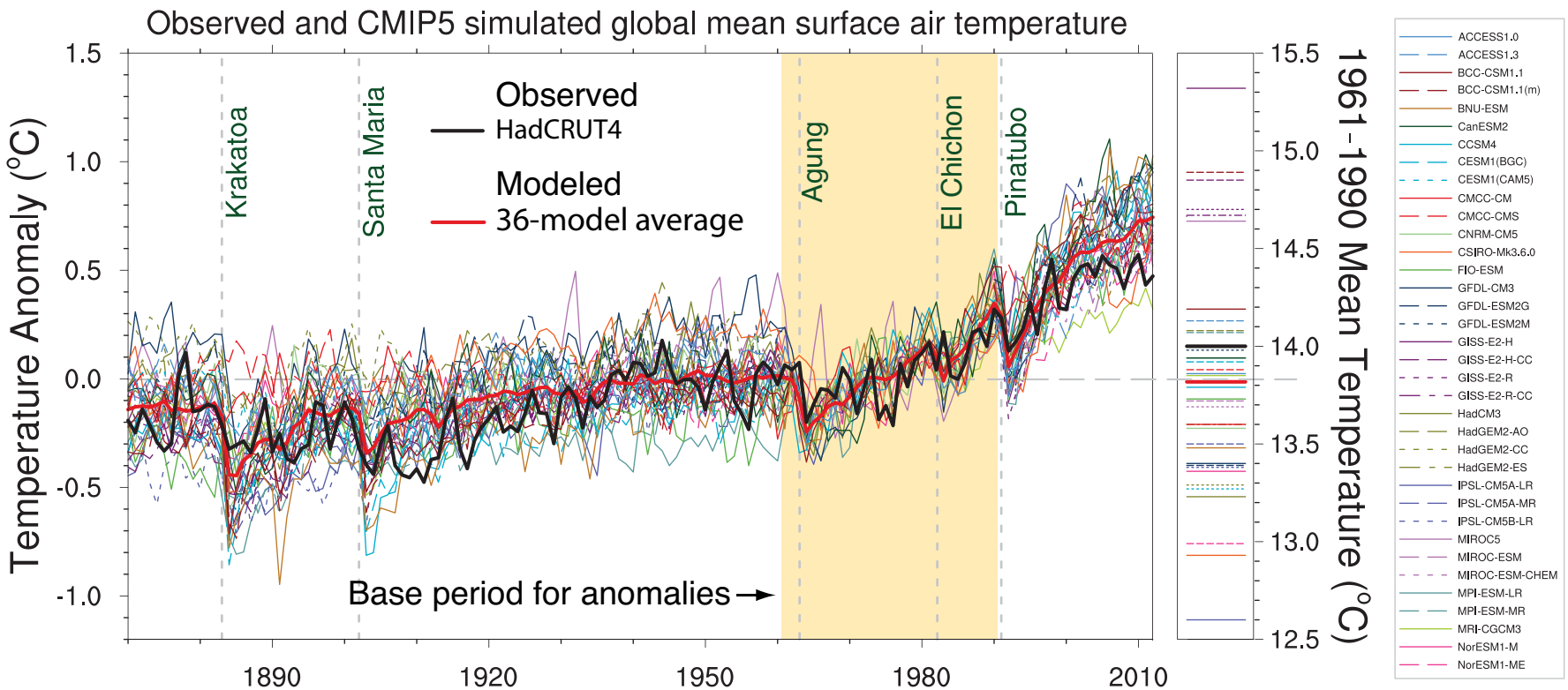
Despite extensive research, climate sensitivity remains ***highly uncertain***.

EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



TEMPERATURE ANOMALY TREND OVER THE 20th CENTURY

Results from 36 climate models and observations, ***showing model offsets***

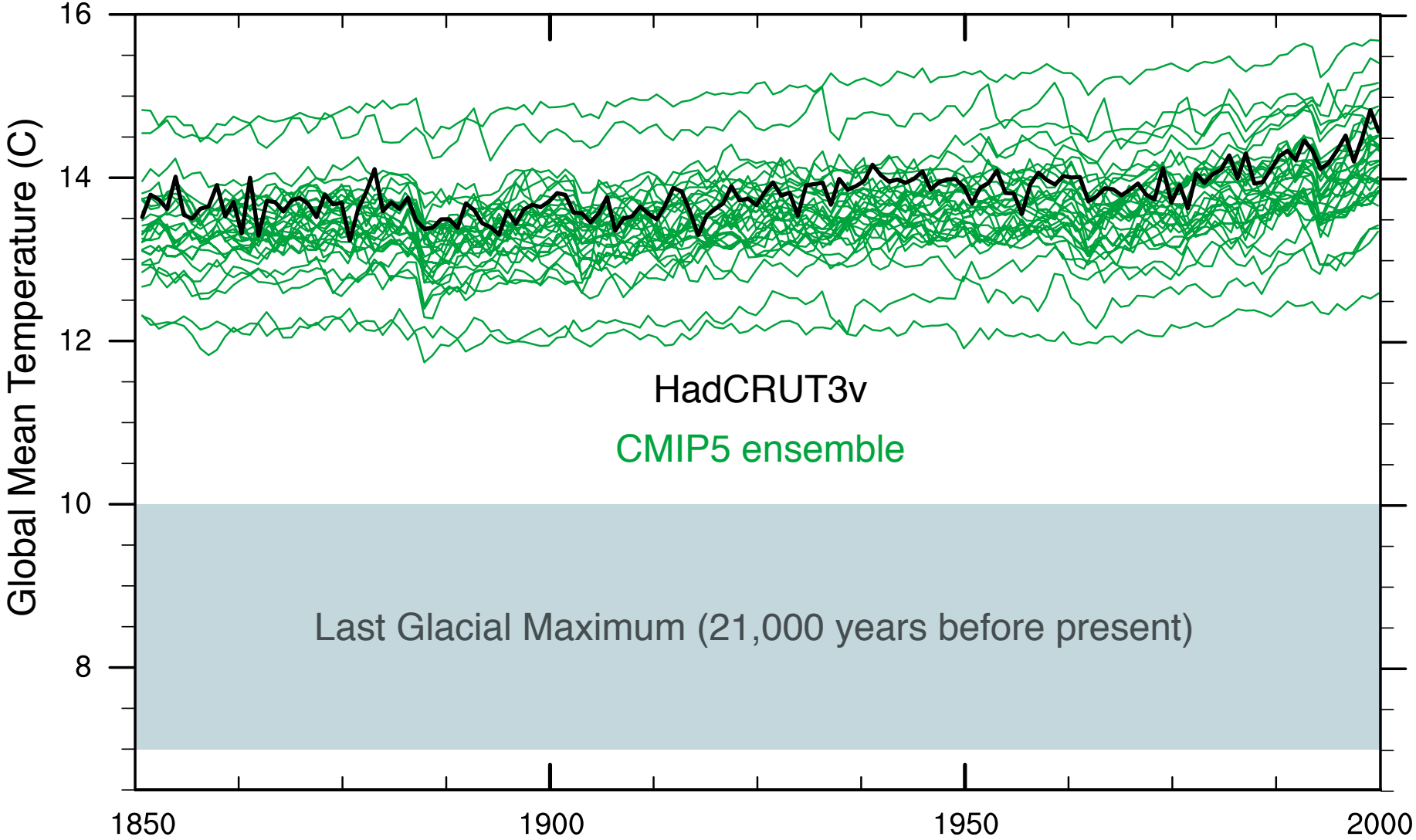


Modified from IPCC AR5 (2013)

"There is ***very high confidence*** that models reproduce the general features of the global-scale annual mean surface temperature increase over the historical period" ***despite model offsets spanning over 2 K, well greater than increase over the record, 0.8 K***.

GLOBAL MEAN SURFACE TEMPERATURE 1850-2000

Measurements and Coupled Atmosphere Ocean Models

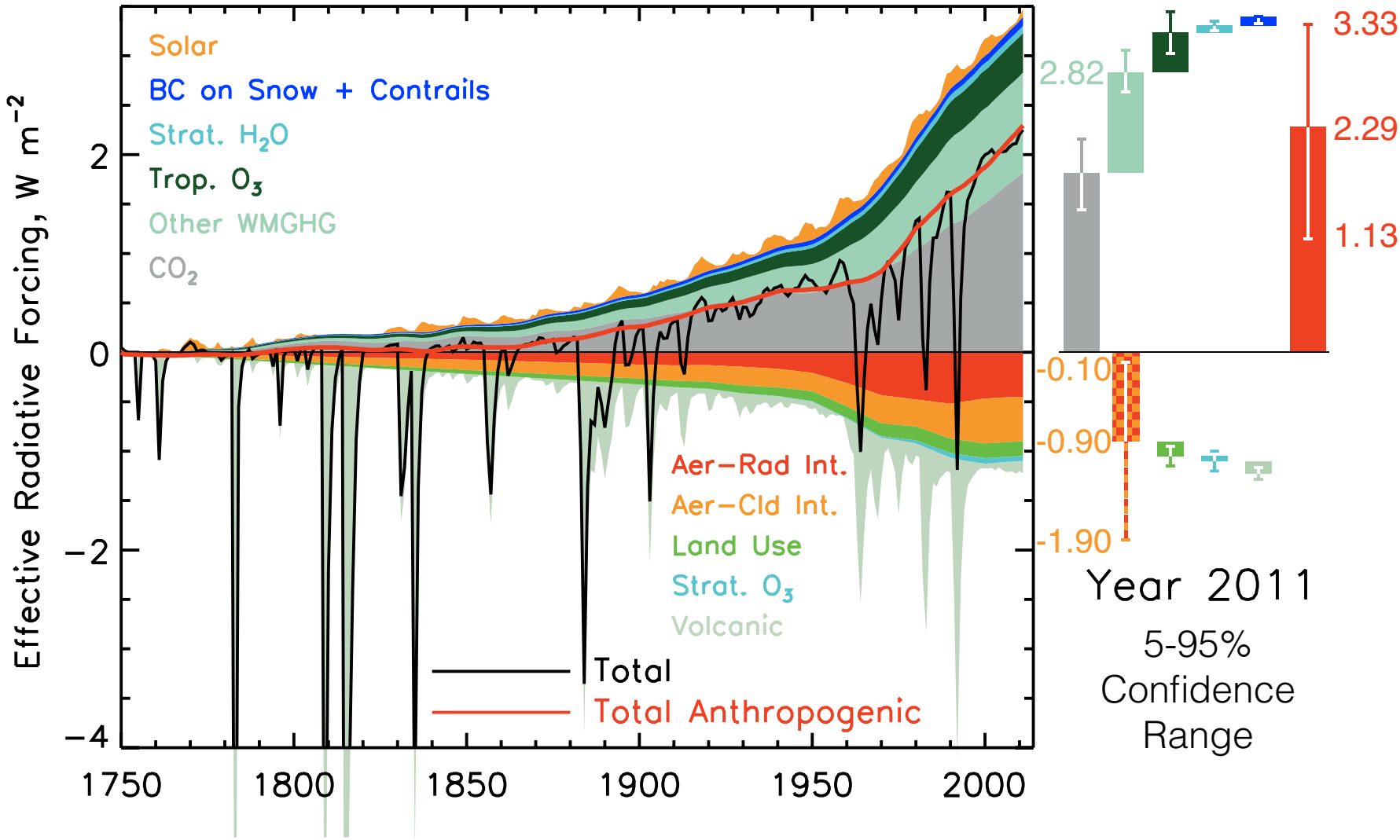


Mauritsen, Stevens, Roeckner, et al. 2012

Spread is substantial relative to observed warming and to warming since last LGM.

RADIATIVE FORCING IN ANTHROPOCENE

Total forcing



IPCC AR5 (2013)

Uncertainty in total forcing, about a factor of 3, is due largely to aerosols.

EARTH'S ENERGY BUDGET

Net energy flux at TOA ≡ Planetary heating rate = Forcing at TOA − Response coefficient · Change in surface temp

$$N \equiv \frac{dH}{dt} = F - \lambda \cdot \Delta T_s$$

At new steady state: $N = 0; \quad \Delta T_s(\infty) = \frac{F}{\lambda}$

"Equilibrium" sensitivity: $S_{eq}[\mathrm{K}/(\mathrm{W\ m^{-2}})] \equiv \lambda^{-1}; \quad \Delta T_s(\infty) = S_{eq} F$

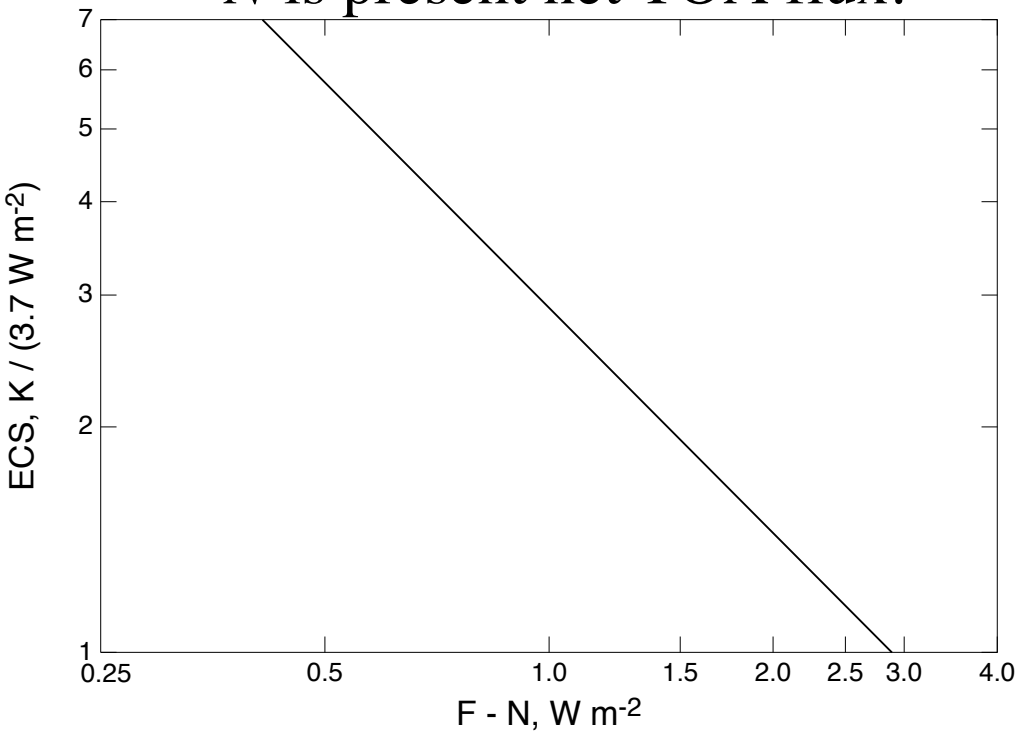
In general: $\Delta T_s(t) = S_{eq}(F - N); \quad S_{eq} = \frac{\Delta T_s(t)}{F - N}$

Equilibrium climate sensitivity (steady-state response to sustained 2 × CO_2 forcing) ECS $[\mathrm{K}/(3.7\ \mathrm{W\ m^{-2}})] \equiv S_{eq} \times (3.7\ \mathrm{W\ m^{-2}})$

EXPECTED RELATION BETWEEN ECS AND FORCING

$$\mathrm{ECS} = (3.7\ \mathrm{W\ m^{-2}}) \times S_{\mathrm{eq}} = (3.7\ \mathrm{W\ m^{-2}}) \frac{\Delta T_{\mathrm{s}}}{F - N}$$

ΔT_{s} and F are temperature change and forcing over 20th century.
N is present net TOA flux.



ECS vs $F - N$ is straight line on log-log plot; slope = -1.

ΔT_{s} over 20th century, 0.78 K; net TOA flux N, 0.44 W m^{-2} (*IPCC AR5*).

EXPECTED RELATION BETWEEN ECS AND FORCING

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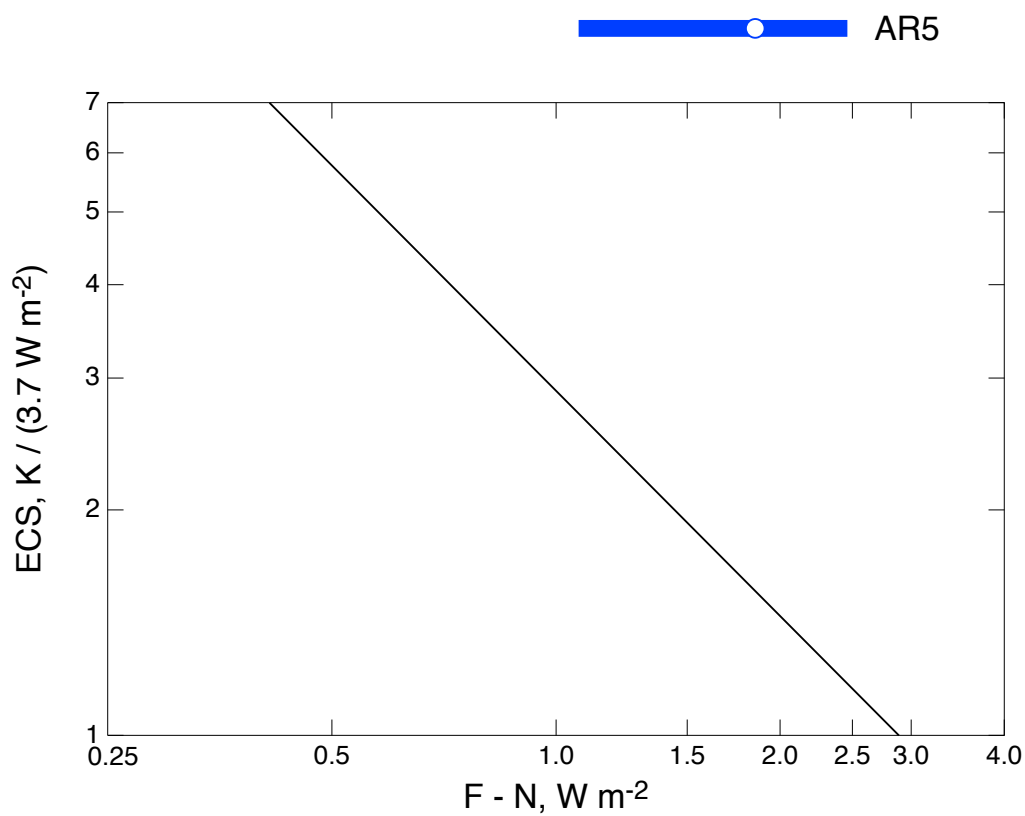

Forcing (best estimate and central 66% likelihood range) from IPCC Fifth Assessment Report (2013), AR5.

EXPECTED RELATION BETWEEN ECS AND FORCING

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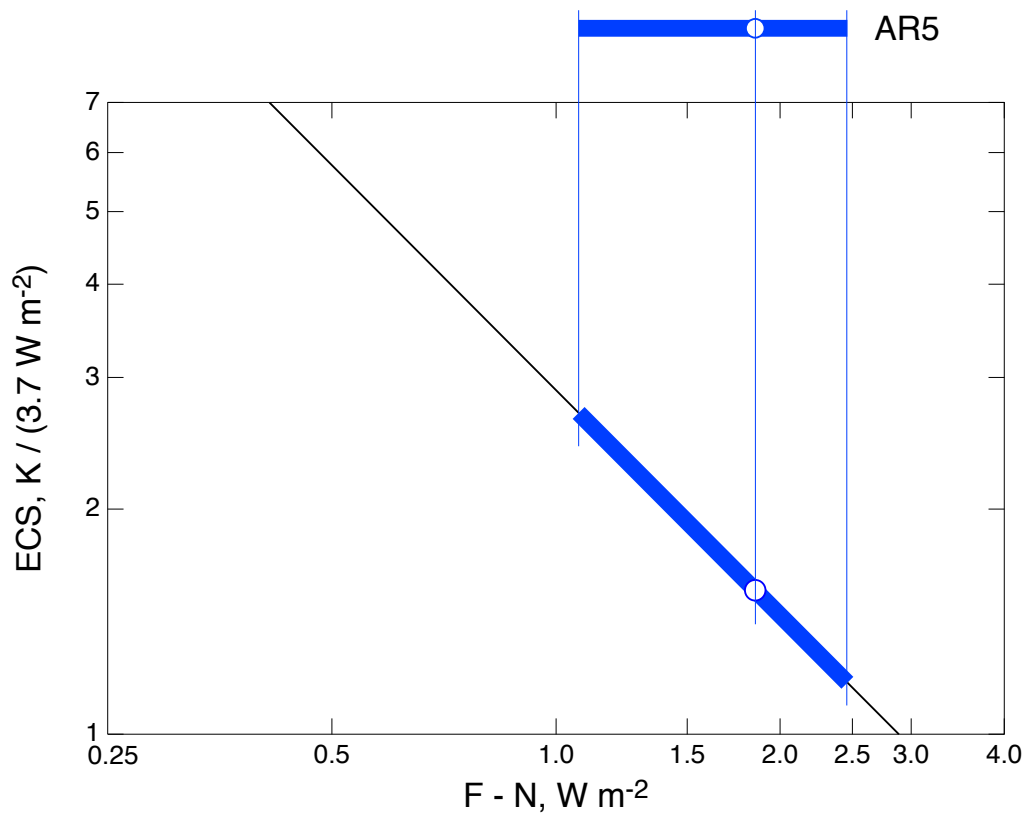
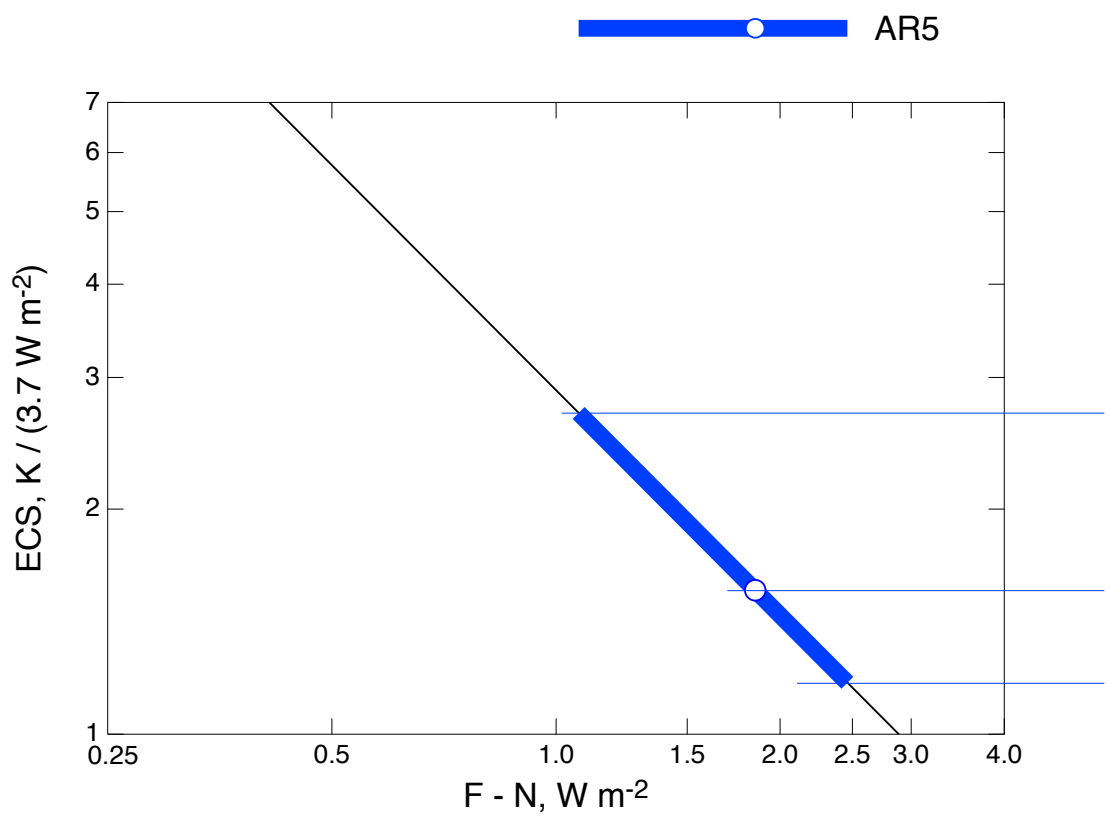


Project forcing onto ECS vs $F - N$ to obtain consistent ECS range.

EXPECTED RELATION BETWEEN ECS AND FORCING

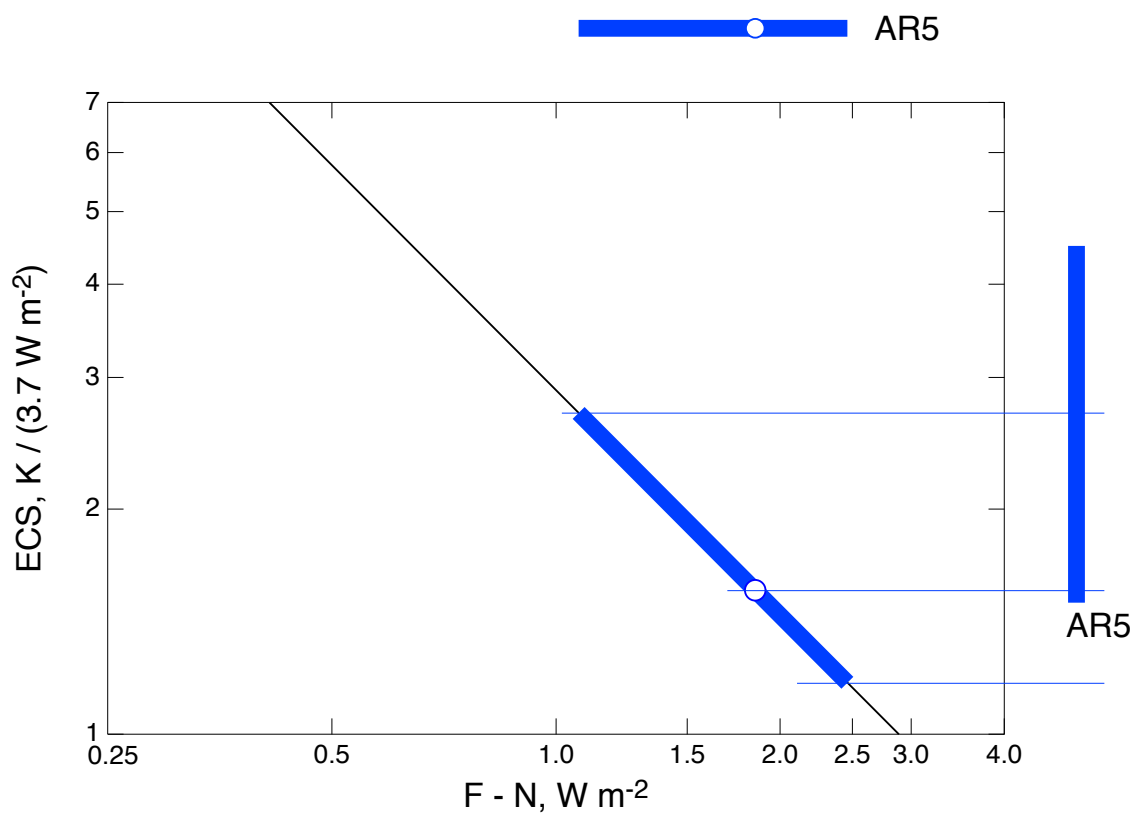
$$\mathrm{ECS} = (3.7\ \mathrm{W\ m^{-2}}) \times S_{\mathrm{eq}} = (3.7\ \mathrm{W\ m^{-2}}) \frac{\Delta T_{\mathrm{s}}}{F - N}$$



Transfer consistent ECS range to vertical scale.

EXPECTED RELATION BETWEEN ECS AND FORCING

$$\mathrm{ECS} = (3.7\ \mathrm{W\ m^{-2}}) \times S_{\mathrm{eq}} = (3.7\ \mathrm{W\ m^{-2}}) \frac{\Delta T_{\mathrm{s}}}{F - N}$$



ECS range consistent with "likely" forcing range, 1.2 – 2.7 K, is much lower than assessed "likely" ECS range, 1.5 – 4.5 K.

EXPECTED RELATION BETWEEN ECS AND FORCING

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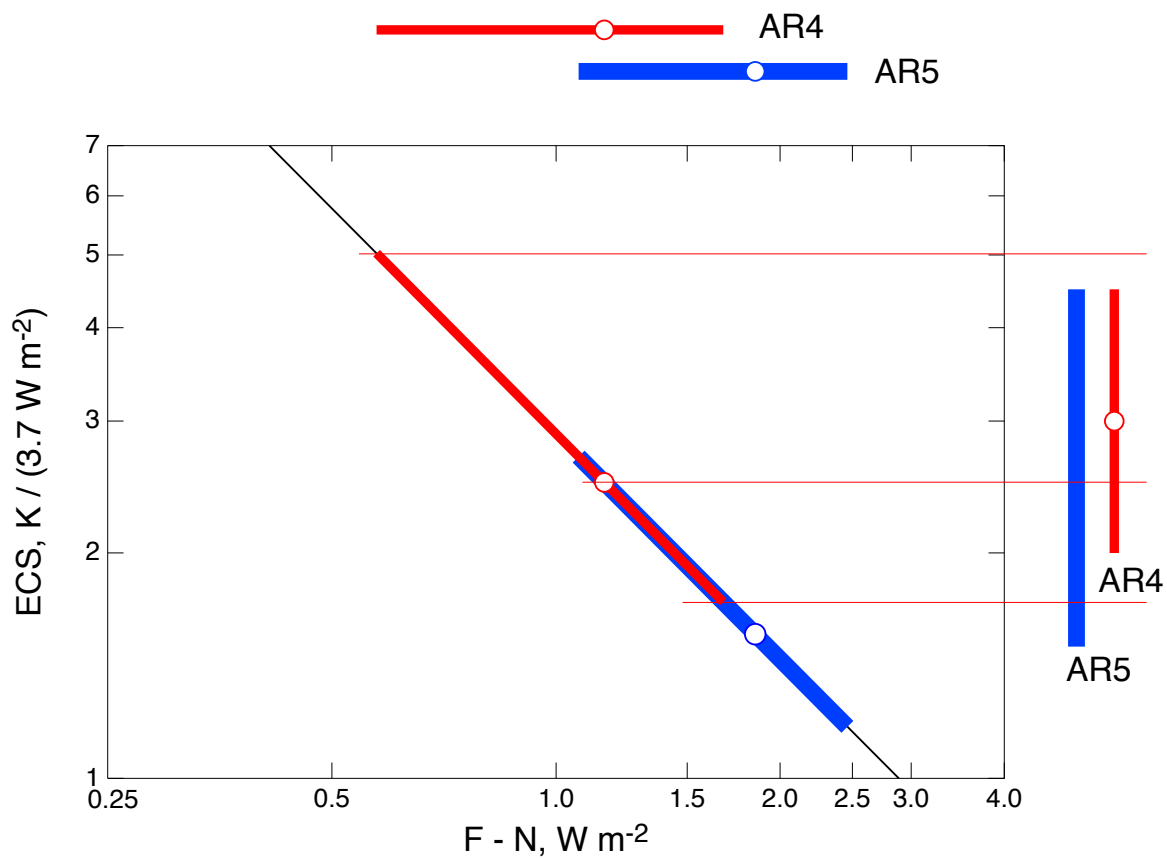

AR4 (2007) is more internally consistent than AR5.

Forcing in AR5 is much greater than in AR4.

EXPECTED RELATION BETWEEN ECS AND FORCING

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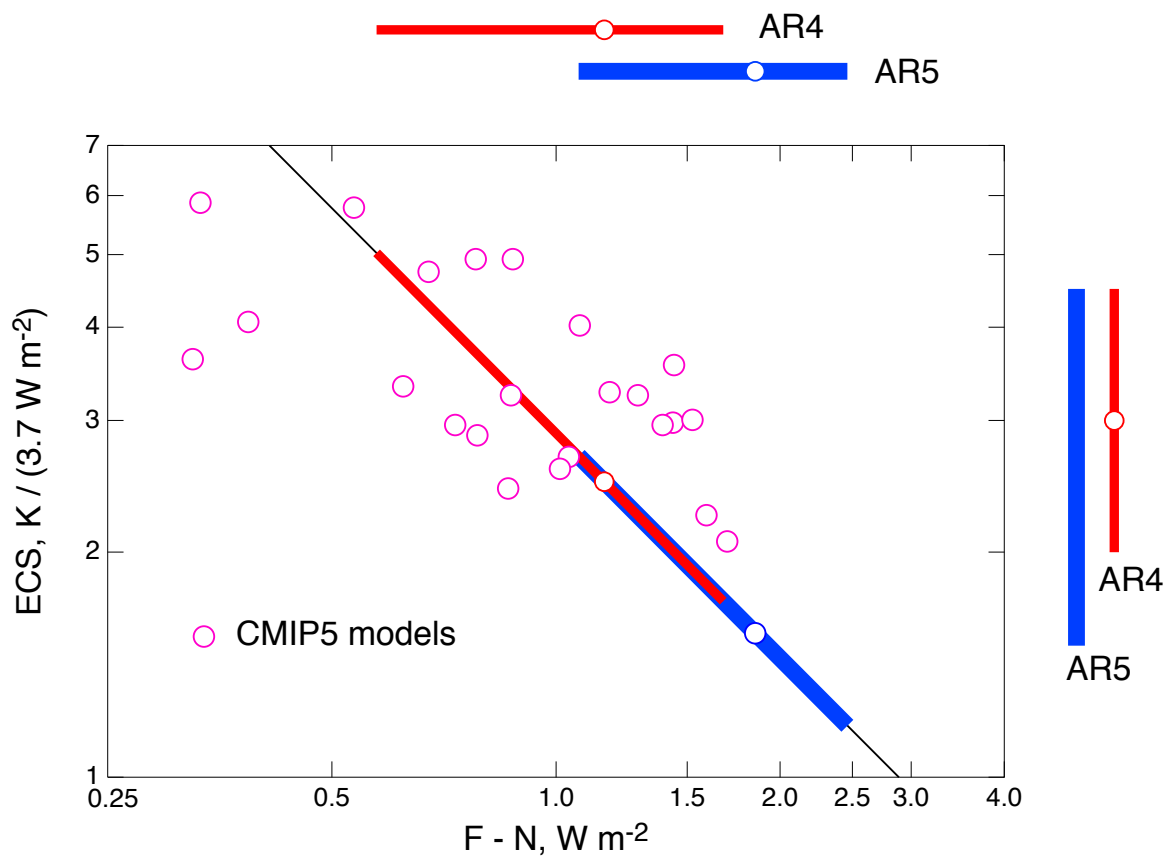


Forcings in CMIP5 models are lower than AR5 range and sensitivities higher. ***Forcings and sensitivities are anticorrelated across models***.

COMMITTED WARMING

For forcing by long-lived greenhouse gases only, relative to preindustrial

Gedanken experiment: Cease emissions from fossil fuel combustion and related activity. Committed warming is resulting temperature change, relative to preindustrial climate.

How much warming is Earth committed to from ***forcing only by LLGHGs*** (residence time > 10 years: CO_2, CH_4, N_2O, CFCs), above preindustrial, in atmosphere at present?

$$F_{\mathrm{LLGHG}} = 2.82 \text{ W m}^{-2}$$

Compare forcing by doubled CO2:

$$F_{2\times} = 3.7 \text{ W m}^{-2}$$

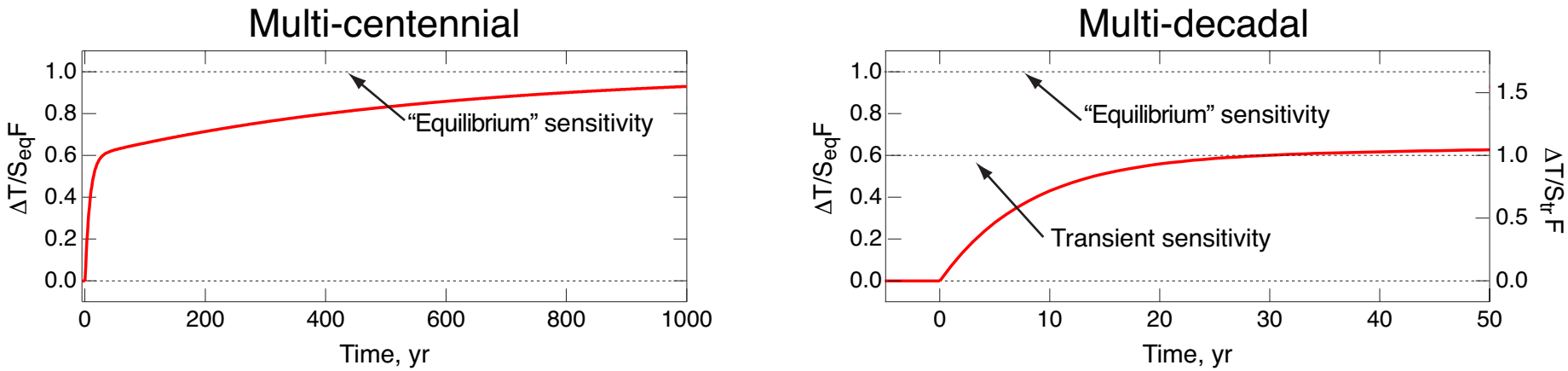
Exclude effect of offsetting forcing by tropospheric aerosols (residence time ~ 1 week).

"EQUILIBRIUM" vs COMMITTED WARMING

For forcing by long-lived greenhouse gases only, relative to preindustrial

$$\Delta T_s(\infty) = S_{eq} F_{LLGHG}; \qquad S_{eq} = \frac{\text{ECS}}{3.7\ \text{W m}^{-2}}$$

S_{eq} is "equilibrium" sensitivity of Earth's climate system.



Schwartz, Surv. Geophys., 2012

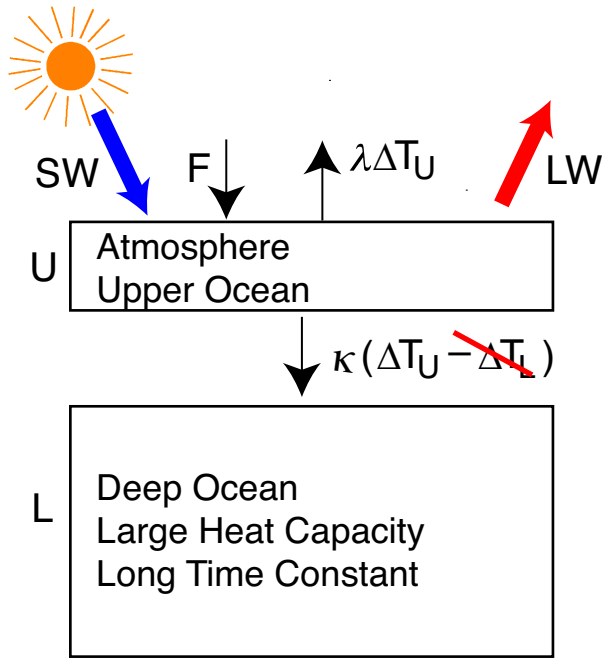
Time to reach steady state temperature is long compared to atmospheric residence times of LLGHGs and time scales of interest.

On decadal scale system reaches quasi steady state described by ***transient sensitivity***.

"Equilibrium" sensitivity yields overestimate of committed warming.

TRANSIENT SENSITIVITY

Two-compartment climate model



Deep ocean provides a sink of heat, parallel to increased longwave radiation at the TOA.

At short times deep ocean sink is constant.

Temperature of upper compartment rapidly reaches quasi steady state described by ***transient sensitivity***: $\Delta T_{\mathrm{cmt}} = S_{\mathrm{tr}} F_{\mathrm{LLGHG}}$

TRANSIENT SENSITIVITY

Alternative approaches to determining transient sensitivity

1. From assessed ***equilibrium sensitivity***:

$$S_{\mathrm{tr}} = \frac{1}{\dfrac{1}{\boldsymbol{S}_{\mathbf{eq}}} + \dfrac{N_{\mathrm{obs}}}{\Delta T_{\mathrm{obs}}}}$$

2. From assessed ***twentieth century forcing***:

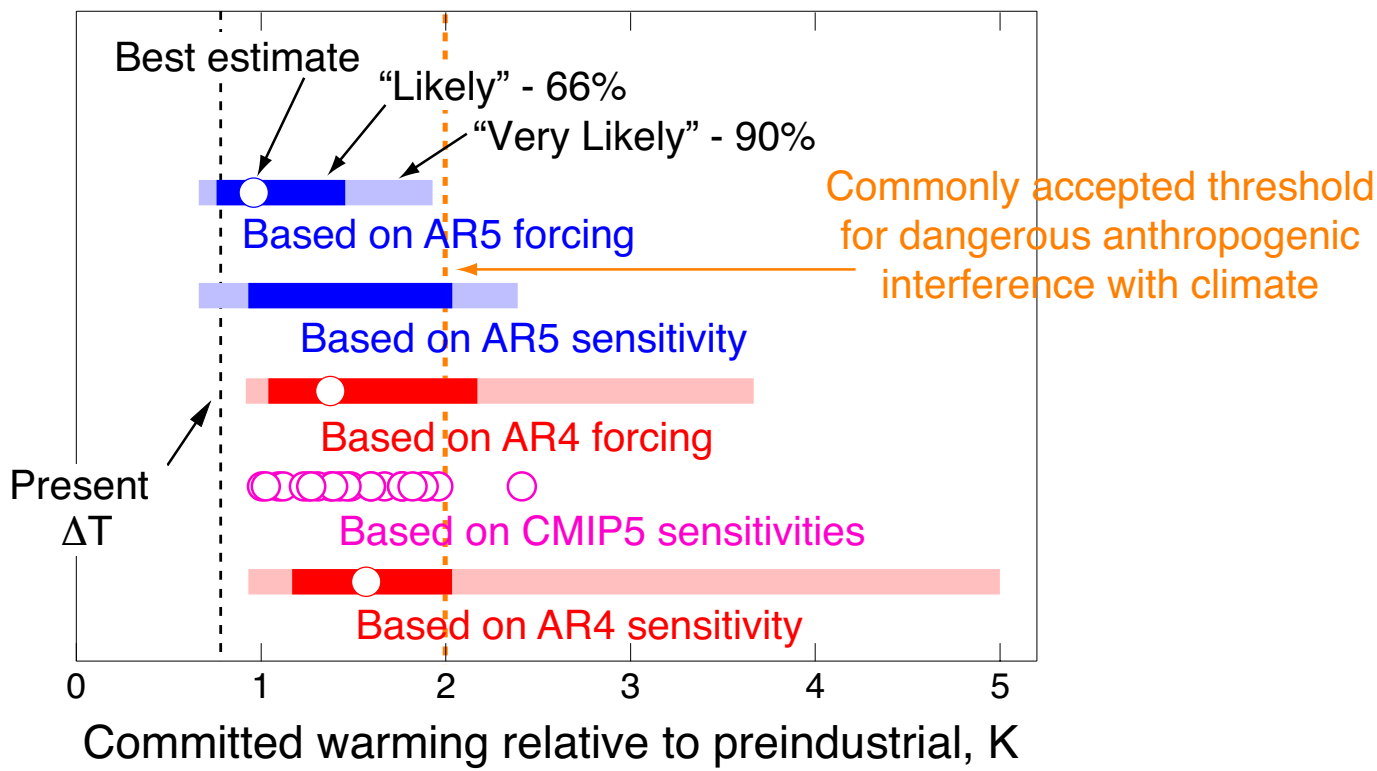
$$S_{\mathrm{tr}} = \frac{\Delta T_{\mathrm{obs}}}{\boldsymbol{F}_{\mathbf{20C}}}$$

Examine dependence of committed warming on ***approach***, and on ***magnitudes of these quantities***.

COMMITTED WARMING

For forcing by long-lived greenhouse gases only

$$\Delta T_{\mathrm{cmt}} = S_{\mathrm{tr}} F_{\mathrm{LLGHG}}; \qquad S_{\mathrm{tr}} = \frac{\Delta T_{\mathrm{obs}}}{F_{\mathbf{20C}}}; \qquad S_{\mathrm{tr}} = \frac{1}{\dfrac{1}{S_{\mathbf{eq}}} + \dfrac{N_{\mathrm{obs}}}{\Delta T_{\mathrm{obs}}}}$$



Current climate models yield substantial range of committed warming.

UNRESOLVED QUESTIONS

1. What is the basis for the ***large reduction in the magnitude of negative aerosol forcing*** and resultant increase in total forcing over the industrial period, as assessed in AR5 versus AR4?

2. Given the large increase in forcing between AR4 and AR5 why is there ***so little decrease in the assessment of ECS between the two reports?***

3. Why, in AR5, is there ***such a great difference between the likely range of ECS***, 1.5 to 4.5 K/(3.7 W m^{-2}), and that inferred from the likely range of forcing, 1.2 to 2.7 K/(3.7 W m^{-2})?

4. Why are the ***forcings employed in the CMIP5 model calculations of climate change over the twentieth century systematically lower*** than those given in the AR5 assessment; what are the ***implications*** of this for interpretation of past climate change and on projections of future climate change obtained with these models?