RELATING CLIMATE FORCINGS AND CLIMATE RESPONSE

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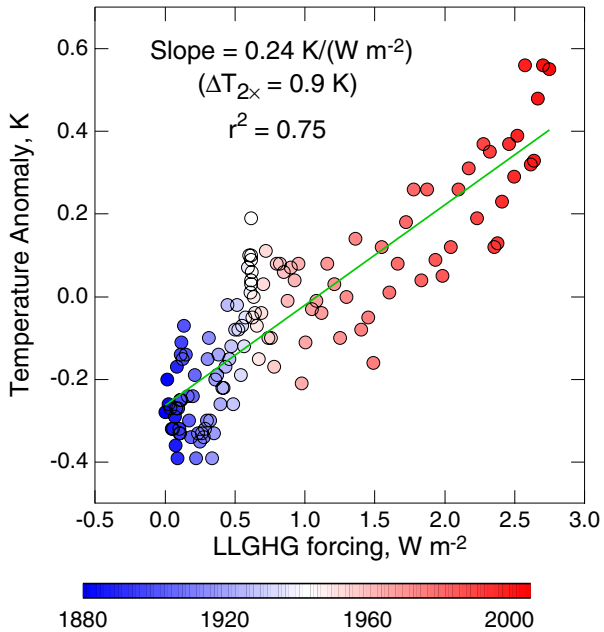
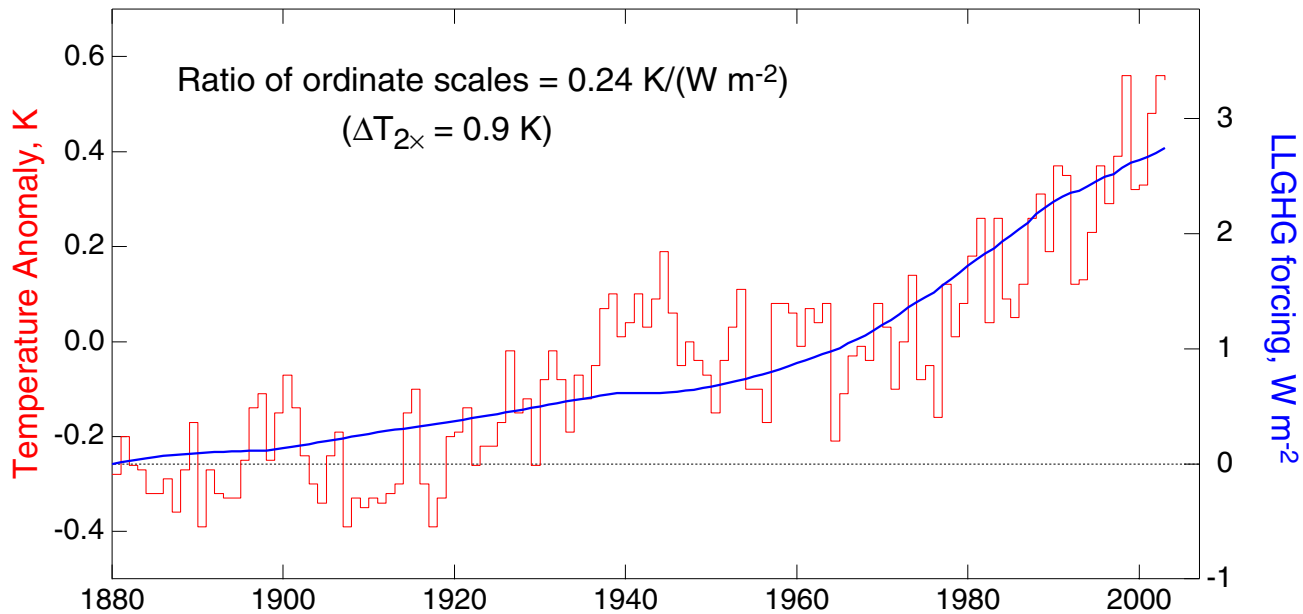
CORRELATION OF FORCING AND GLOBAL MEAN TEMPERATURE

Long-lived greenhouse gases





Forcing, GISS model; Temperature anomaly, GISS

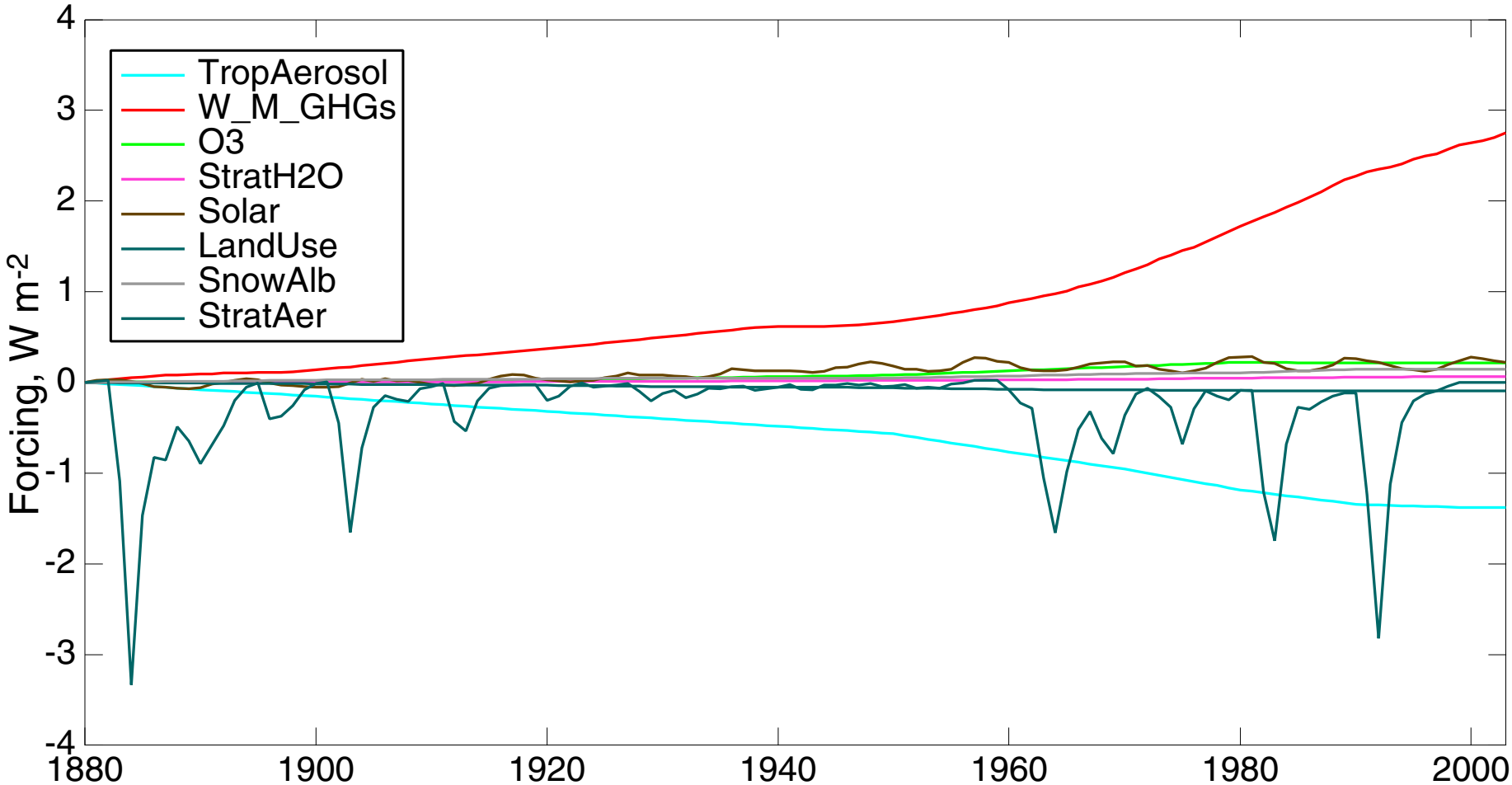
Forcing and temperature change are tightly correlated.

Forcing by GHGs only leads to extremely low climate sensitivity, well below IPCC AR4 range $\Delta T_{2\times} = 2 - 4.5$ K.

Low sensitivity is attributed to lack of inclusion of aerosol forcing and/or non-equilibrium.

FORCINGS IN GISS MODEL

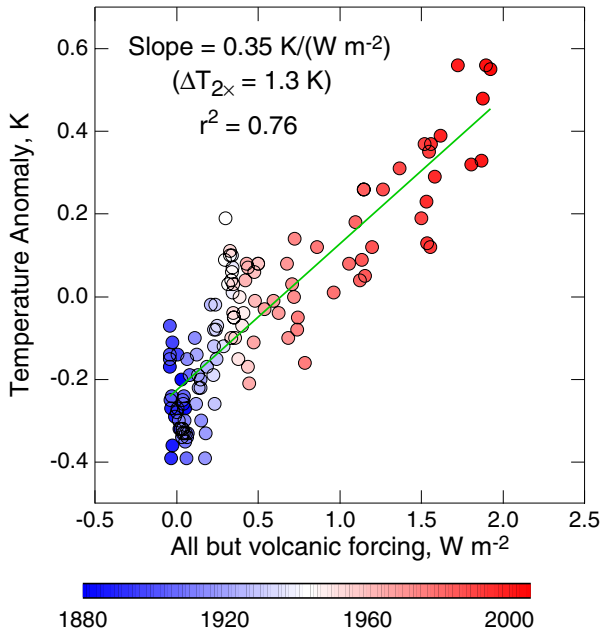
Input into correlation analysis with GMST

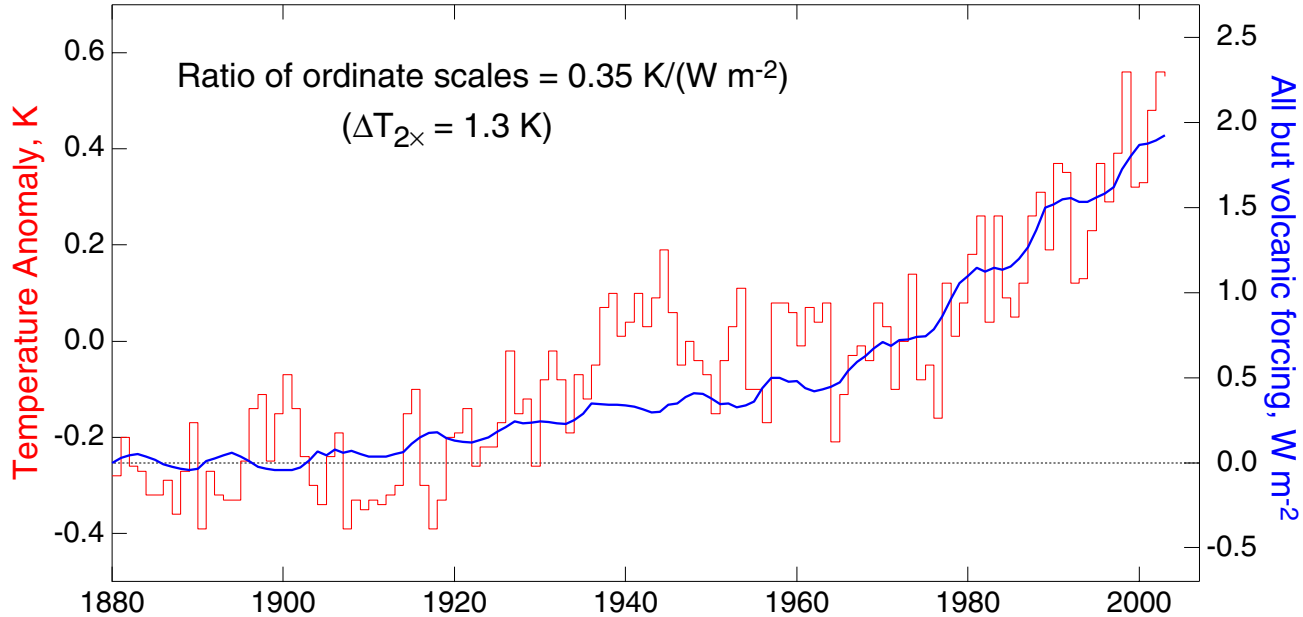


Tropospheric aerosol forcing (Direct + Ind + BC) = -1.4 W m^{-2} (2003).

CORRELATION OF FORCING AND GLOBAL MEAN TEMPERATURE

All forcings except volcanic





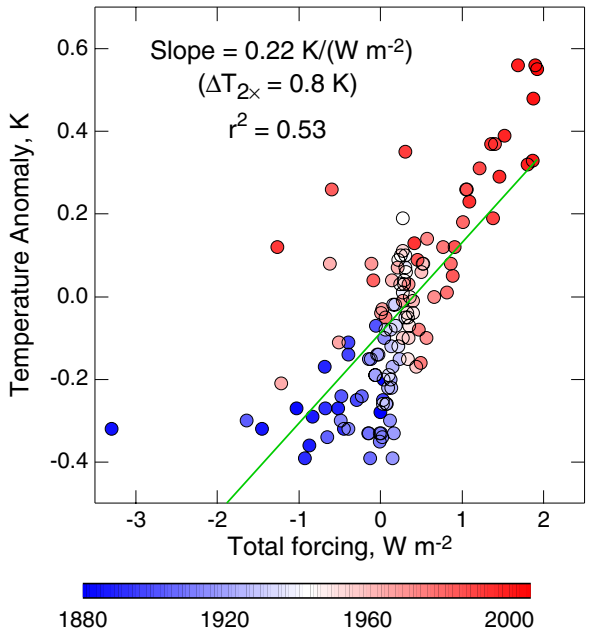
Forcing, GISS model; Temperature anomaly, GISS

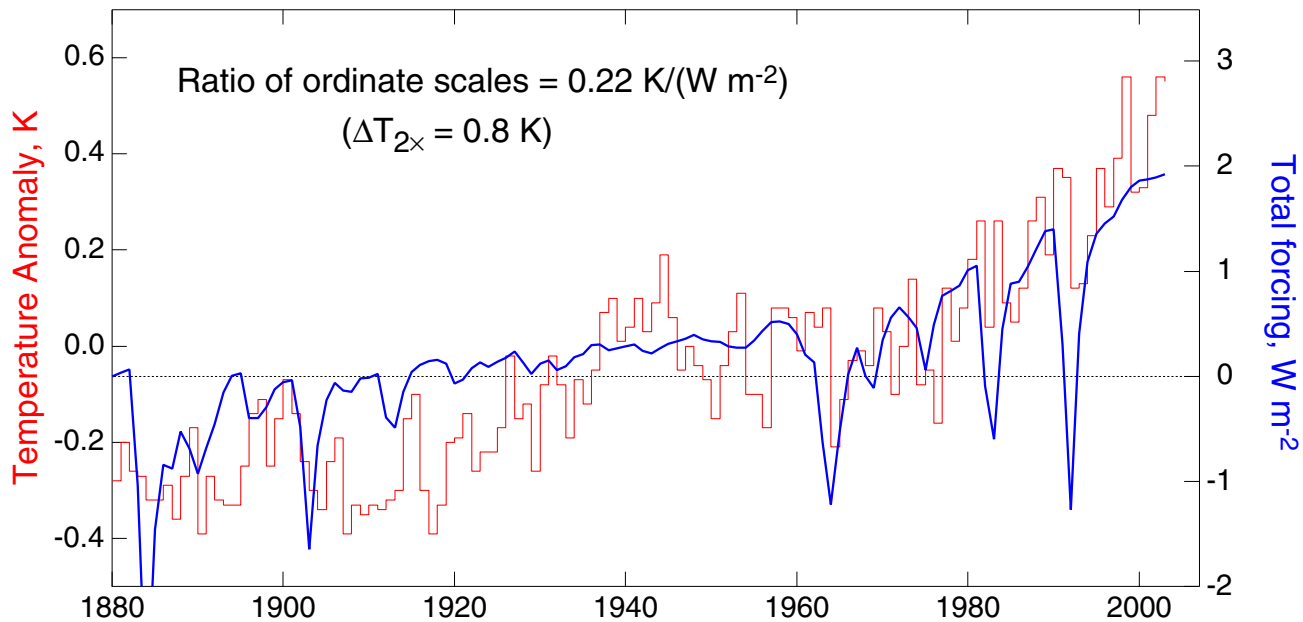
Forcing and temperature change remain tightly correlated.

Sensitivity is somewhat greater.

CORRELATION OF FORCING AND GLOBAL MEAN TEMPERATURE

All forcings





Forcing, GISS model; Temperature anomaly, GISS

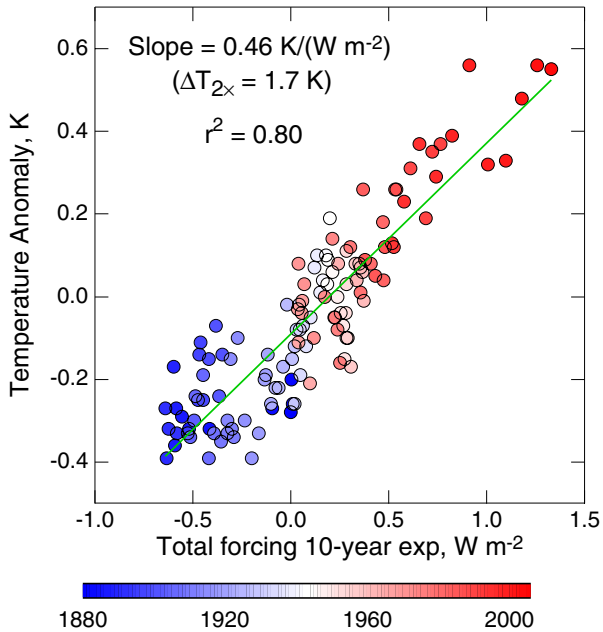
Correlation is much weaker.

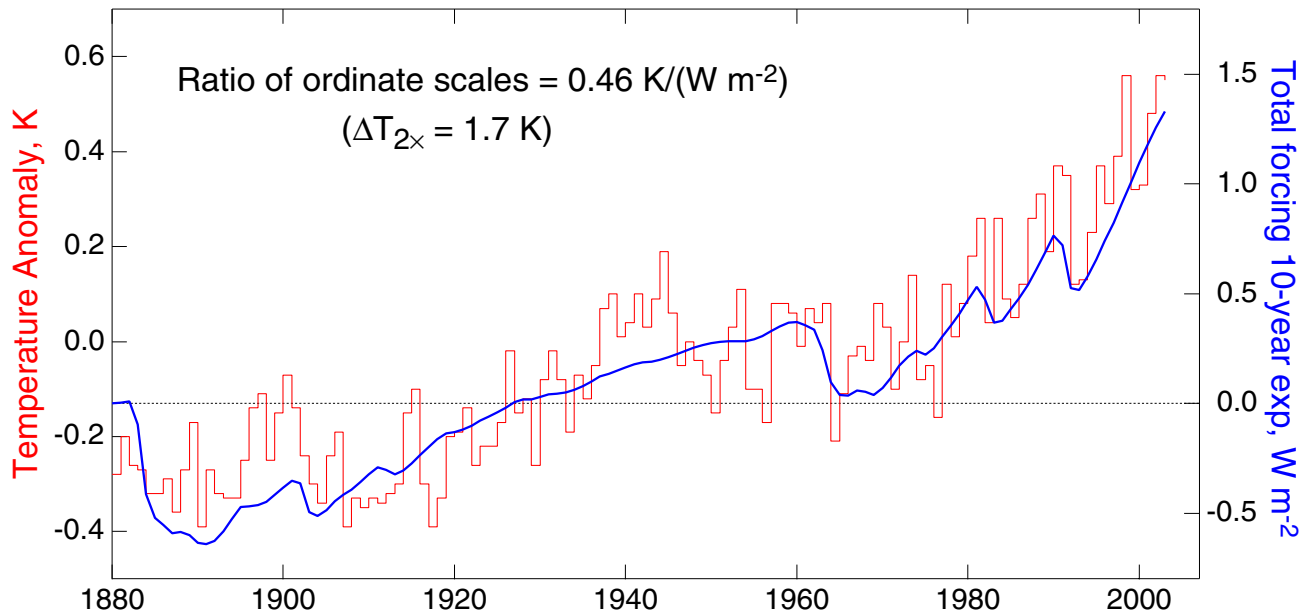
Temperature does not respond rapidly to rapid changes in forcings by stratospheric volcanic aerosols.

Climate sensitivity is quite low, probably because of lack of full response to short-duration forcings.

CORRELATION OF FORCING AND GLOBAL MEAN TEMPERATURE

All forcings, convolved with 10-year exponential





Forcing, GISS model; Temperature anomaly, GISS

Forcing and temperature change are once again tightly correlated.

Sensitivity is increased but still well less than IPCC AR4 range ($\Delta T_{2\times} = 2 - 4.5$ K).

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

Global energy balance: $$\frac{dH}{dt} \equiv N = Q - E$$

H is global heat content $\qquad$ $N \equiv dH / dt$ is net heat flux into planet.

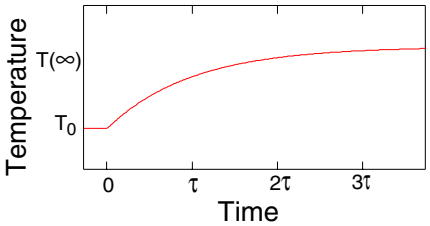
Q is absorbed solar energy $\qquad$ E is emitted longwave flux

Initially system is at radiative steady state ("equilibrium"):

$$N = 0 = Q_0 - E_0$$

Apply step-function forcing F; system responds by change in temperature and resulting change in emitted longwave flux:

$$N = F - \lambda \Delta T(t)$$



At new equilibrium $N = 0$ and $\Delta T = \lambda^{-1} F$; λ^{-1} = equilibrium sensitivity.

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

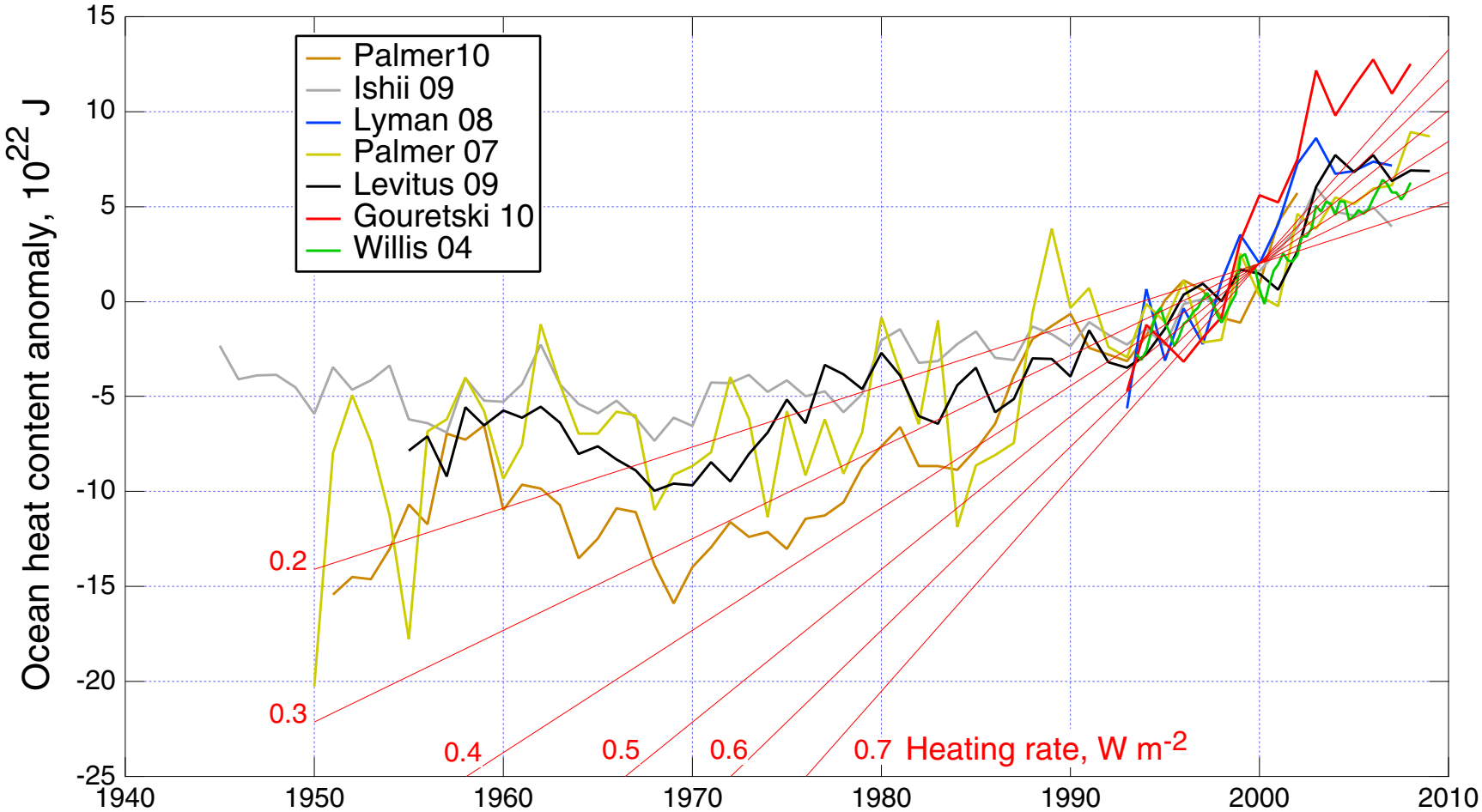
Energy balance equation: $N = F - \lambda \Delta T$

Hence $\lambda = \dfrac{F - N}{\Delta T} = \dfrac{F_{\text{eff}}}{\Delta T}$; $F_{\text{eff}} \equiv F - N$ is *effective forcing* that accounts for heat flux into planet.

Observationally, forcing is proportional to ΔT, $F = \phi \Delta T$.

OCEAN HEAT CONTENT (0 - 700 m)

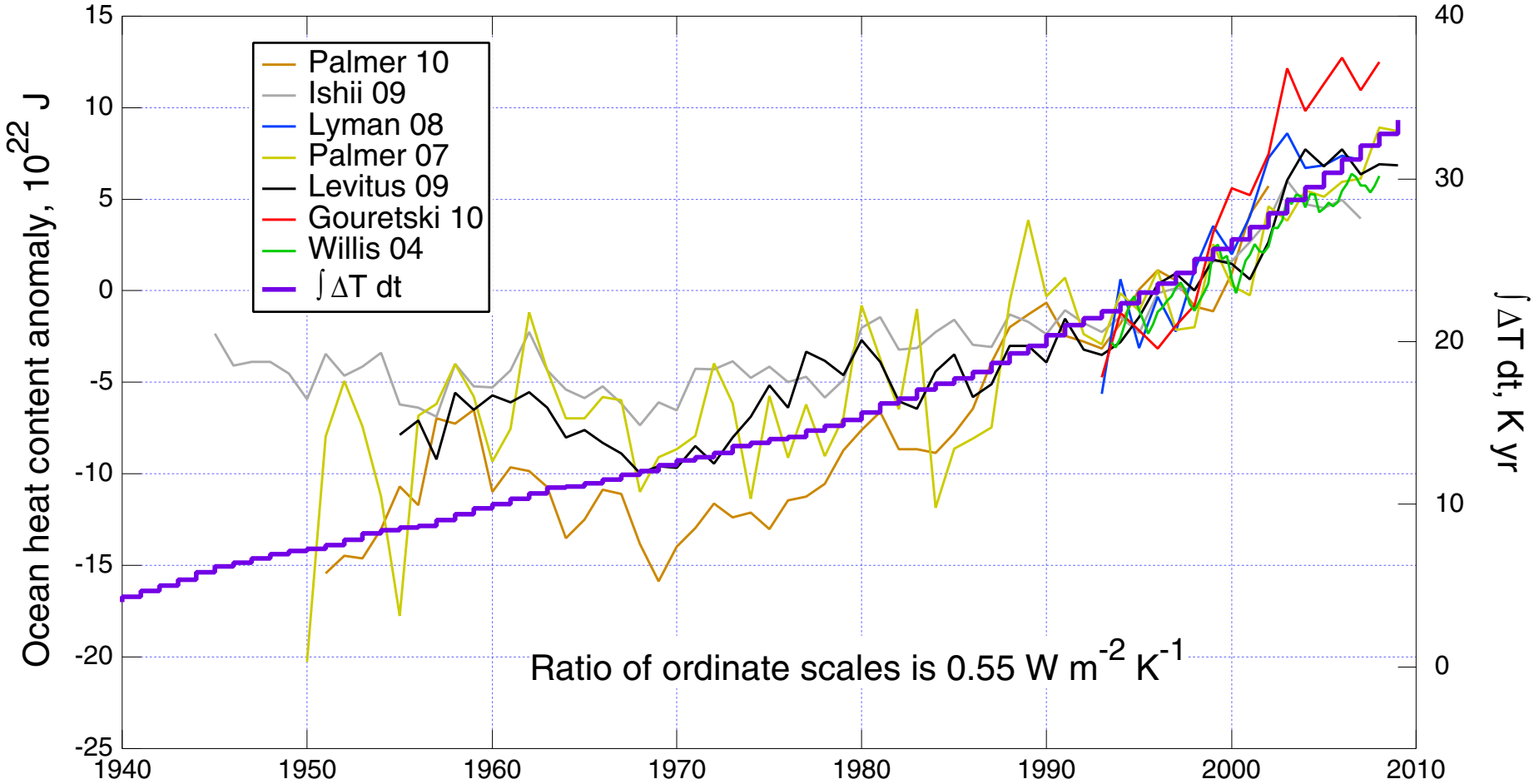
Estimates from multiple analyses



Data available at http://www.ncdc.noaa.gov/bams-state-of-the-climate/2009-time-series/?ts=ohc

Range of slopes, 0.45 ± 0.25 W m^{-2}, brackets most analyses.

CORRELATION OF OCEAN HEAT CONTENT AND INTEGRATED TEMPERATURE ANOMALY



Ocean heat content, NOAA; Temperature anomaly, GISS

Ocean heat content is proportional to integrated temperature increase.

Observationally based ocean heat uptake normalized to temperature increase: $\nu \equiv N/\Delta T = 0.55$ W m^{-2} K^{-1}; for $\Delta T = 0.8$ K, $N = 0.44$ W m^{-2}.

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

Energy balance equation: $N = F - \lambda \Delta T$

Hence $\lambda = \dfrac{F - N}{\Delta T} = \dfrac{F_{\text{eff}}}{\Delta T}$; $F_{\text{eff}} \equiv F - N$ is *effective forcing* that accounts for heat flux into planet.

Observationally, forcing is proportional to ΔT, $F = \phi \Delta T$.

Observationally, energy imbalance is proportional to ΔT, $N = \nu \Delta T$.

$$\lambda = \frac{\phi \Delta T - \nu \Delta T}{\Delta T} = \phi - \nu$$

Determine equilibrium sensitivity from known heat flux and forcing.

Observationally, $\nu = 0.55$ W m^{-2} K^{-1}. ***This seems fairly robust***.

For $\Delta T = 0.8$ K, $N = 0.44$ W m^{-2}.

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

Inverse climate sensitivity: $\lambda = \dfrac{\phi \Delta T - \nu \Delta T}{\Delta T} = \phi - \nu$

Observationally, $\nu = 0.55$ W m^{-2} K^{-1}.

For GISS forcing, $\phi = 2.16$ W m^{-2} K^{-1}.

Hence $\lambda = \phi - \nu = 1.61$ W m^{-2} K^{-1}.

Sensitivity $S = \lambda^{-1} = 0.62$ K/(W m^{-2})

CO_2 doubling temperature $\Delta T_{2\times} = F_{2\times} S = (3.71 \text{ W m}^{-2}) S = 2.3$ K, toward the low end of the IPCC AR4 range (2 – 4 K). However this result depends on the magnitude of the GISS tropospheric aerosol forcing, -1.4 W m^{-2}.

Determination of climate sensitivity by this approach requires confident knowledge of the forcing.

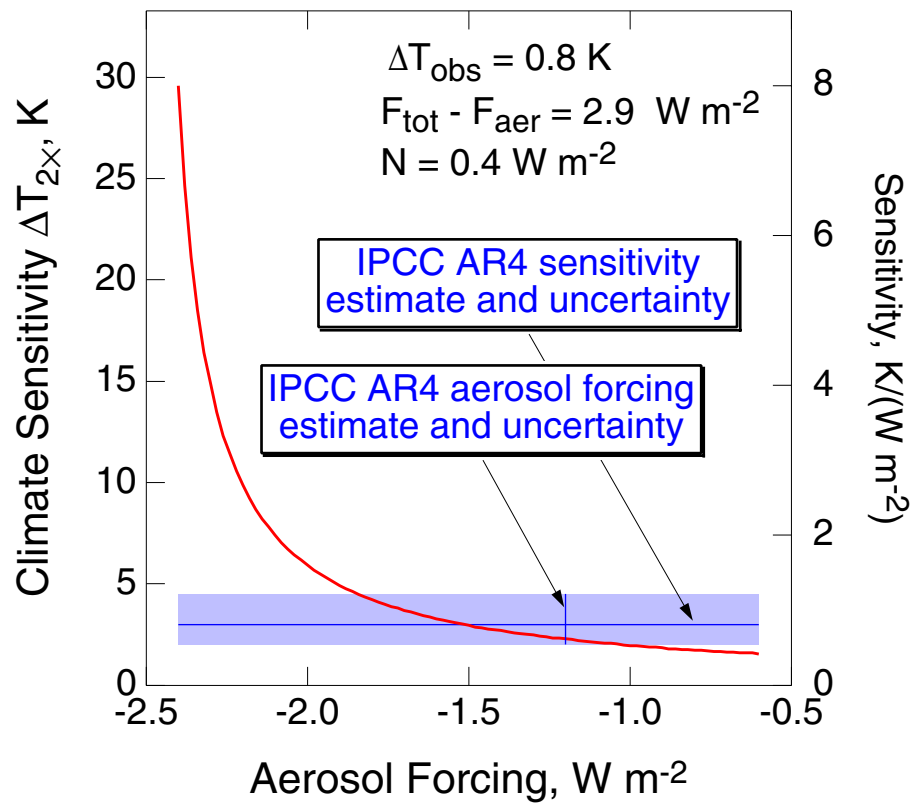
EMPIRICAL DETERMINATION OF EARTH'S CLIMATE SENSITIVITY

Dependence on aerosol forcing

$$S = \frac{\Delta T_{\text{obs}}}{F_{\text{eff}}}$$

$$S = \frac{\Delta T_{\text{obs}}}{F_{\text{tot}} - N}$$

$$S = \frac{\Delta T_{\text{obs}}}{F_{\text{aer}} + (F_{\text{tot}} - F_{\text{aer}}) - N}$$



F_{tot} - F_{aer} is due mainly to LLGHGs.

Heating rate N determined from rate of increase of ocean heat content.

Graph is plotted for uncertainty range of aerosol forcing from IPCC AR4.

Sensitivity increases strongly for aerosol forcing > 2 W m^{-2}.