EARTH'S HEAT UPTAKE COEFFICIENT AND TRANSIENT AND EQUILIBRIUM CLIMATE SENSITIVITIES

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viewgraphs available at www.ecd.bnl.gov/steve

SOME SIMPLE QUESTIONS ABOUT CLIMATE CHANGE

How much has ***Global Mean Surface Temperature*** (GMST) increased over the industrial period?

What is the magnitude of ***forcing*** over the industrial period?

What is Earth's ***climate sensitivity***?

What is the expected ***equilibrium increase*** in GMST?

Why hasn't GMST increased as much as expected?

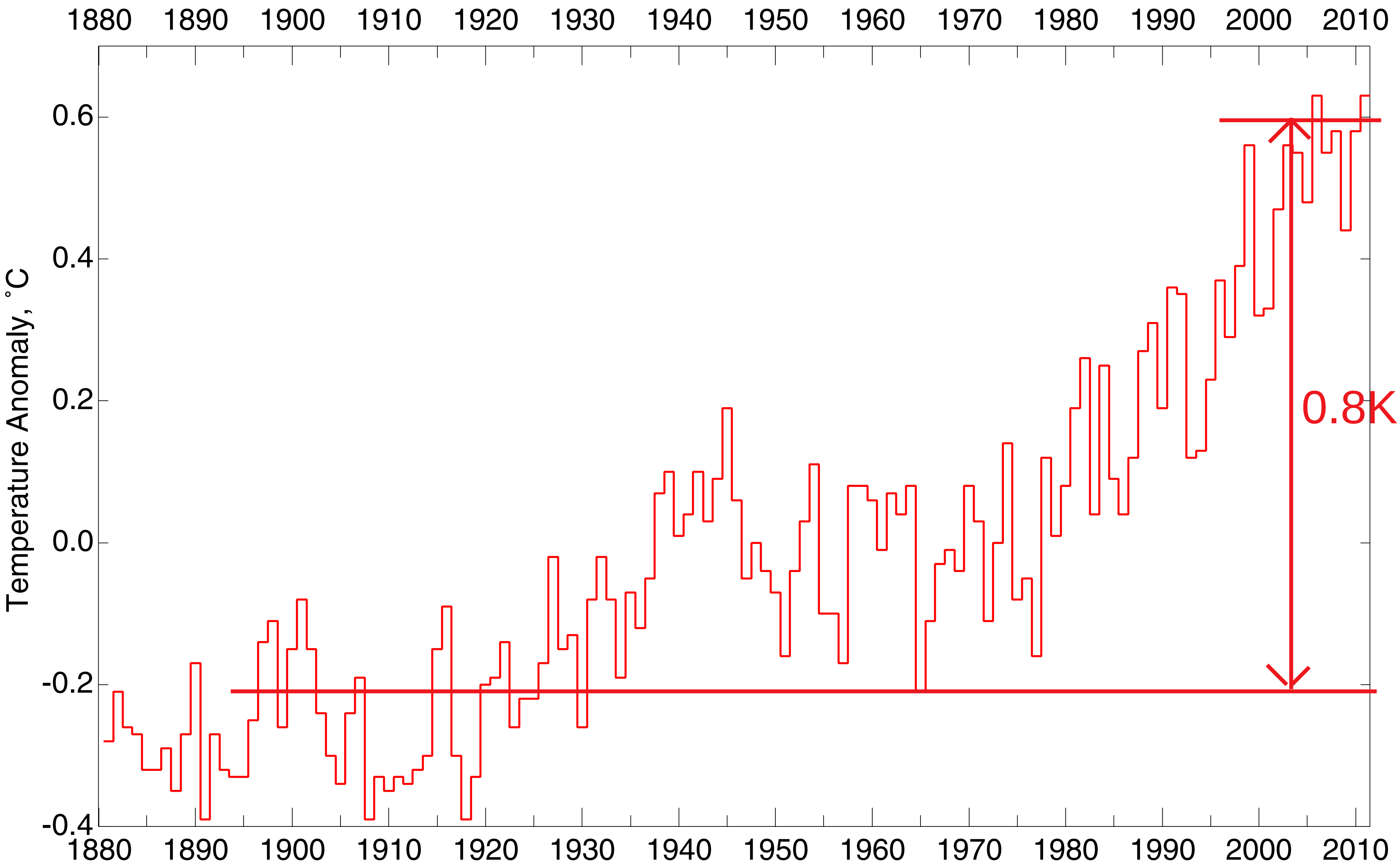
How much of this is due to ***time lag of response*** of the climate system? What are the ***time constants*** of the system?

How much is due to ***offsetting forcing by tropospheric aerosols***?

What is the magnitude of the ***planetary energy imbalance***?

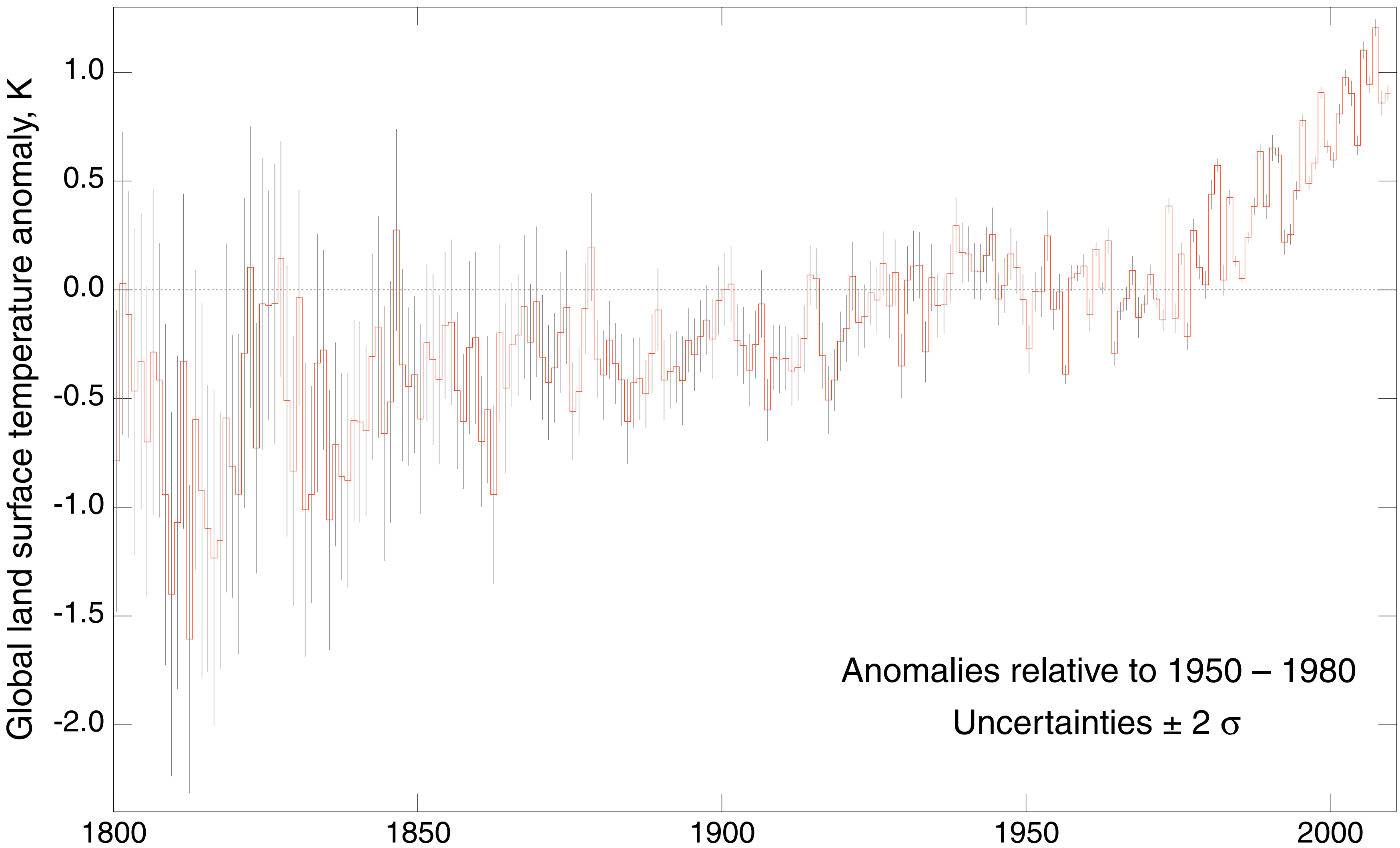
How much more warming is "***in the pipeline***" – committed warming?

GLOBAL ANNUAL TEMPERATURE ANOMALY, 1880-2010



Data: Goddard Institute for Space Studies

GLOBAL LAND SURFACE TEMPERATURE ANOMALY

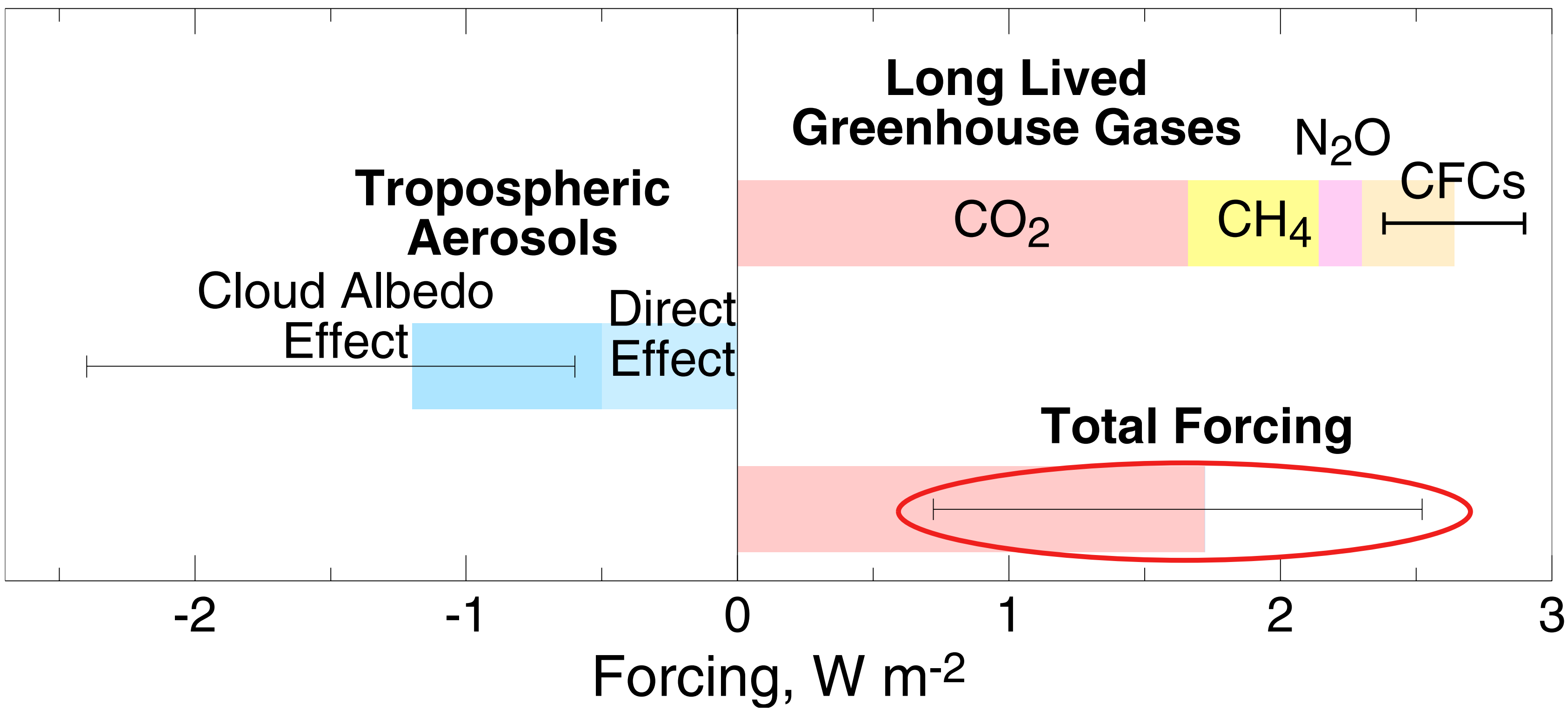


Muller et al. (Berkeley Earth Project), submitted, 2011

Independent analysis confirms increase in temperature over 20*th* century.

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)



Aerosol forcing may offset much of the greenhouse gas forcing.

Uncertainty in total forcing is dominated by uncertainty in aerosol forcing.

EQUILIBRIUM CLIMATE SENSITIVITY

Equilibrium change in global mean surface temperature = Climate sensitivity × Forcing

$$\Delta T = S_{\text{eq}} \times F$$

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

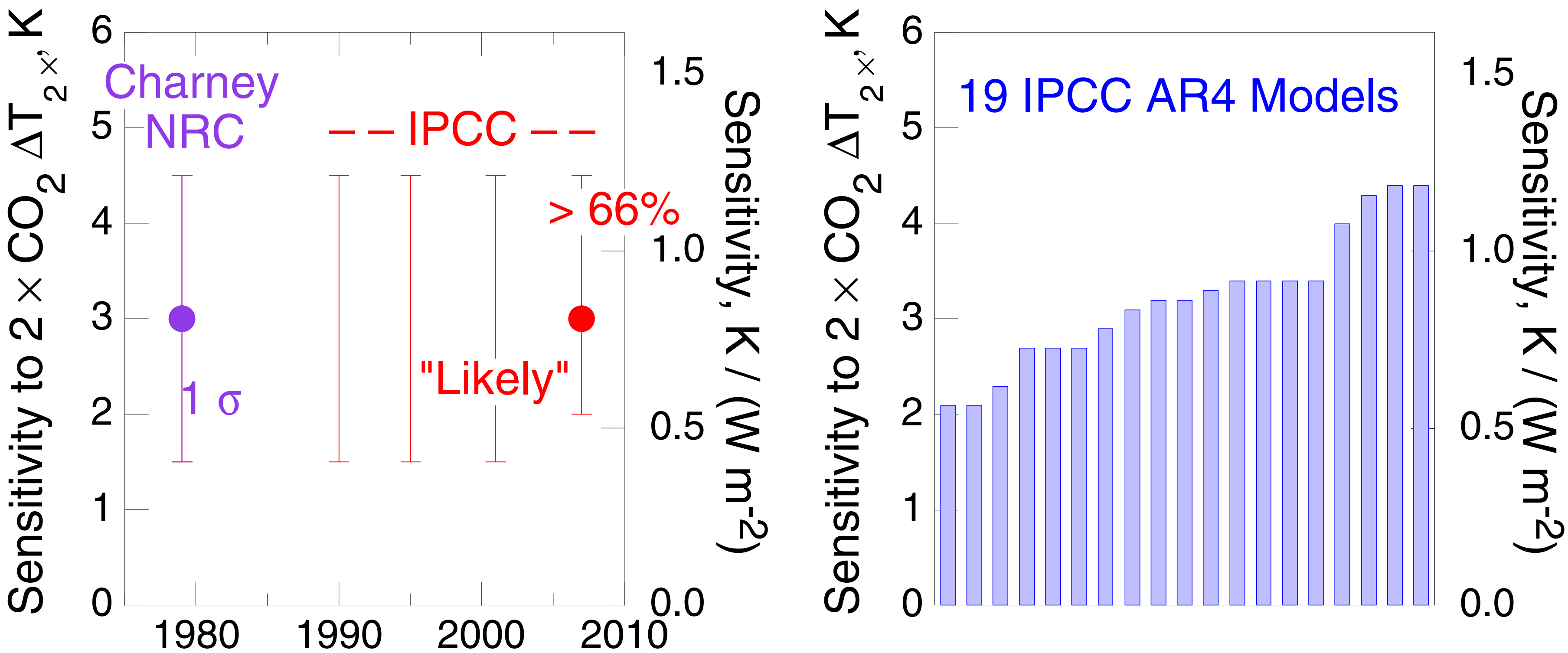
Sensitivity is commonly expressed as "CO_2 doubling temperature"

$$\Delta T_{2\times,\text{eq}} \equiv S_{\text{eq}} \times F_{2\times}$$

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 and current climate models



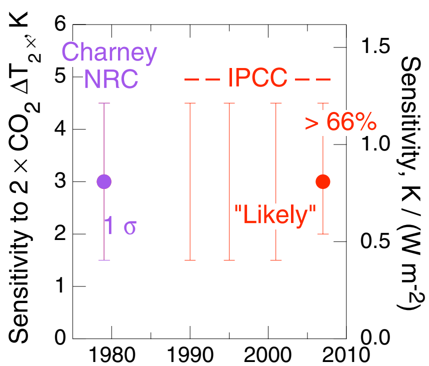
Current estimates of Earth's climate sensitivity are centered about a CO_2 doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty.

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

EQUILIBRIUM TEMPERATURE CHANGE

Climate sensitivity × Forcing = Equilibrium change in global mean surface temperature

$$S \times F \overset{?}{=} \Delta T$$



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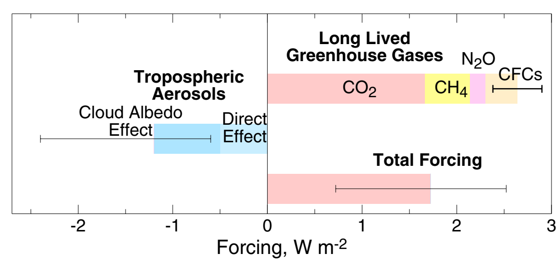
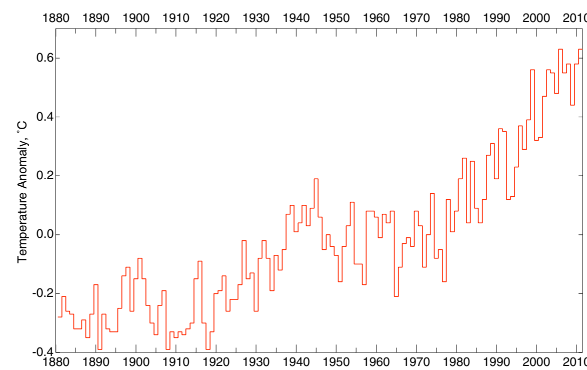


$\overset{?}{=}$

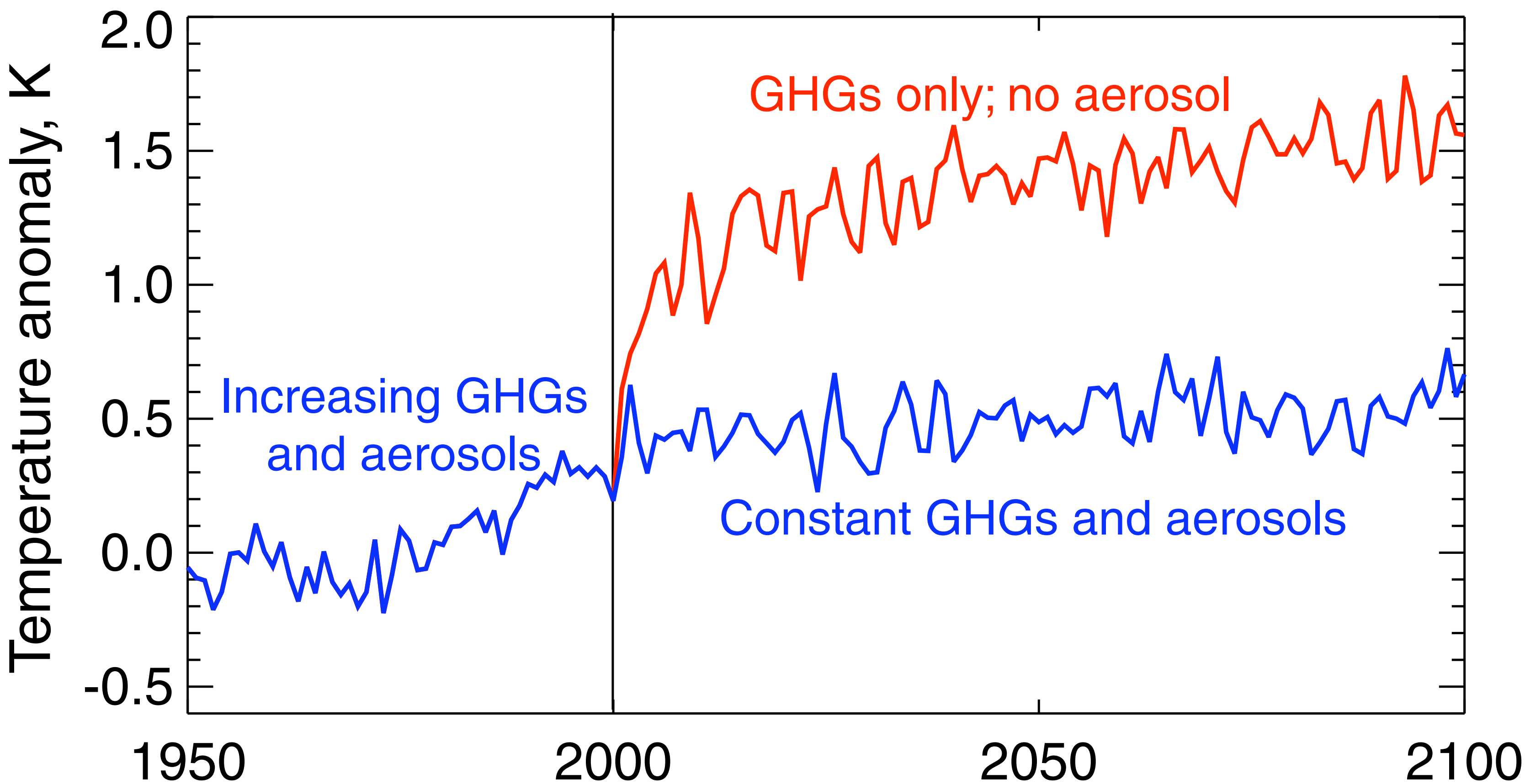


$$\begin{array}{c}0.54\\0.81\\1.21\end{array}\ \mathrm{K/(W\ m^{-2})} \times \begin{array}{c}1.1\\1.6\\2.0\end{array}\ \mathrm{W\ m^{-2}} = \begin{array}{c}0.7\\1.3\\2.0\end{array}\ \mathrm{K}$$

(~1σ)

GLOBAL TEMPERATURE RESPONSE TO TURNING OFF AEROSOL EMISSIONS

Experiment with ECHAM-5 GCM

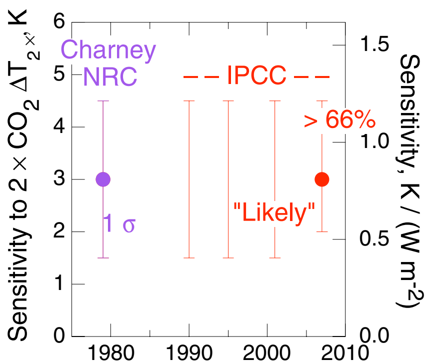


Modified from Brasseur and Roeckner, GRL, 2005

For constant GHGs and aerosols, temperature remains near year 2000 value.
Without aerosol offset to GHG forcing temperature rapidly increases.
However the magnitude of the aerosol offset is unknown.

For forcing by long-lived greenhouse gases only

$$\Delta T_{\mathrm{LLGHG}} = S \times F_{\mathrm{LLGHG}}$$



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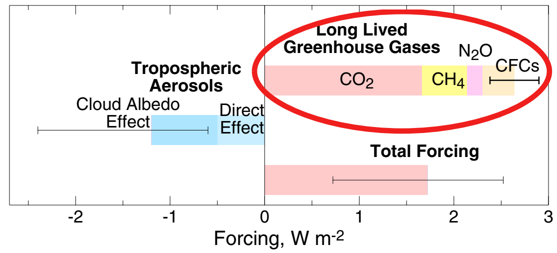
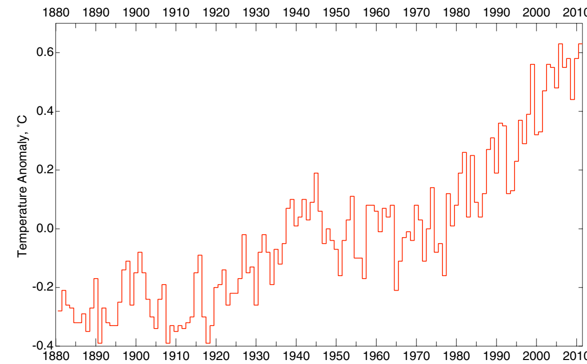


? =

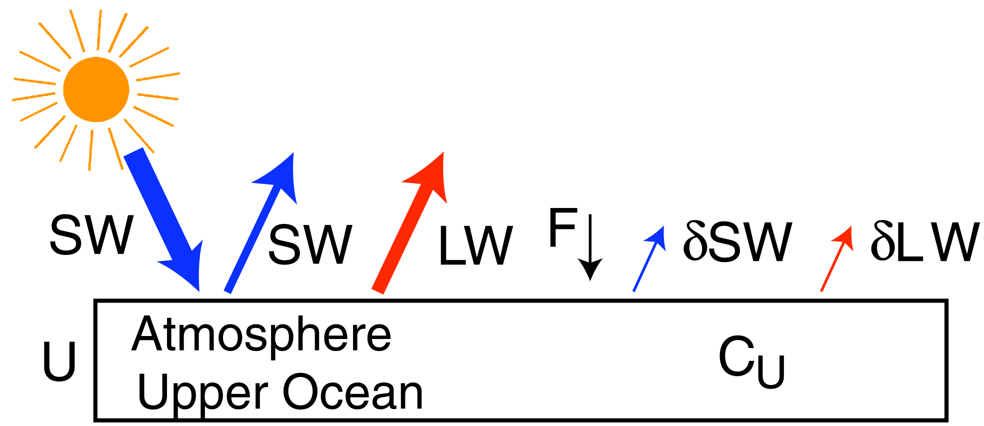


$$\begin{matrix}0.54\\0.81\\1.21\end{matrix}\ \mathrm{K/(W\ m^{-2})} \times \begin{matrix}2.47\\2.60\\2.73\end{matrix}\ \mathrm{W\ m^{-2}} = \begin{matrix}1.4\\2.1\\3.2\end{matrix}\ \mathrm{K}$$

Improved knowledge of forcings and climate sensitivity is essential for informed policymaking.

OBSERVATIONALLY BASED DETERMINATION OF CLIMATE SENSITIVITY VIA ENERGY BALANCE MODELS

Single compartment climate model



Energy conservation in the climate system:

$$\frac{dH}{dt} \equiv N = Q - E$$

H = planetary heat content;

N = net heating rate of planet;

Q = absorbed shortwave at TOA;

E = emitted longwave at TOA.

Unperturbed steady state (equilibrium) climate:

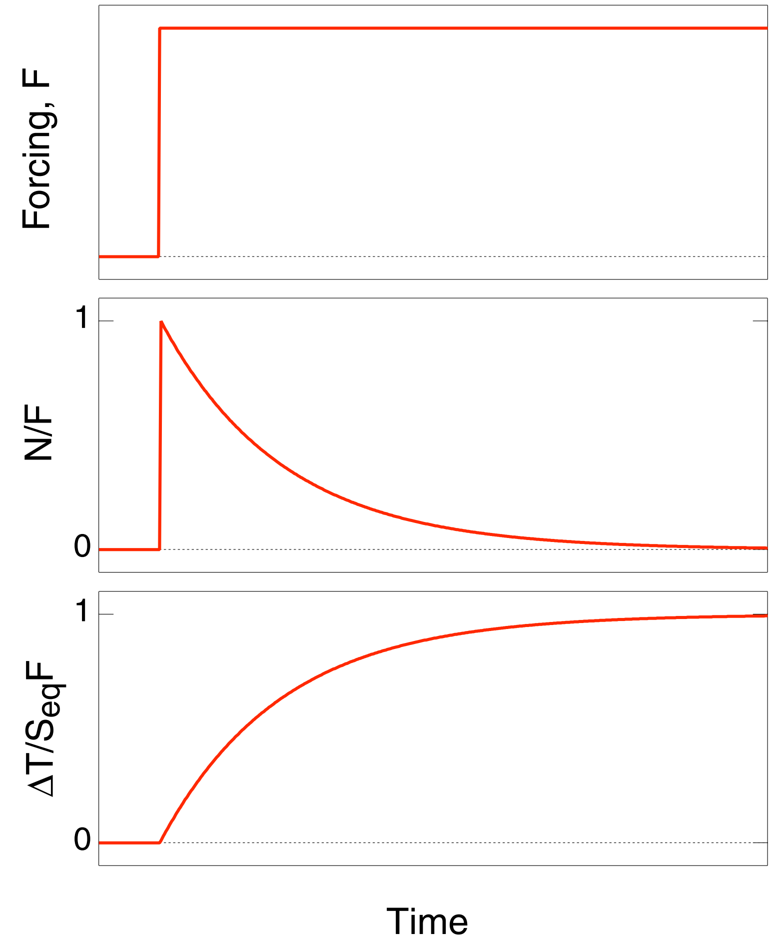
$$N = 0; \qquad Q_0 = E_0$$

Net heating rate with external forcing F applied:

$$N(t) = Q(t) - E(t) + F(t)$$

Initially after onset of forcing

$$Q = Q_0; \quad E = E_0; \quad N = F$$



Climate response to forcing

$$N(t) = F(t) + \frac{\partial(Q-E)}{\partial T}\Delta T(t)$$

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

where $\lambda \equiv -\frac{\partial(Q-E)}{\partial T}$ is *climate response coefficient.*

λ is a geophysical property of Earth's climate system.

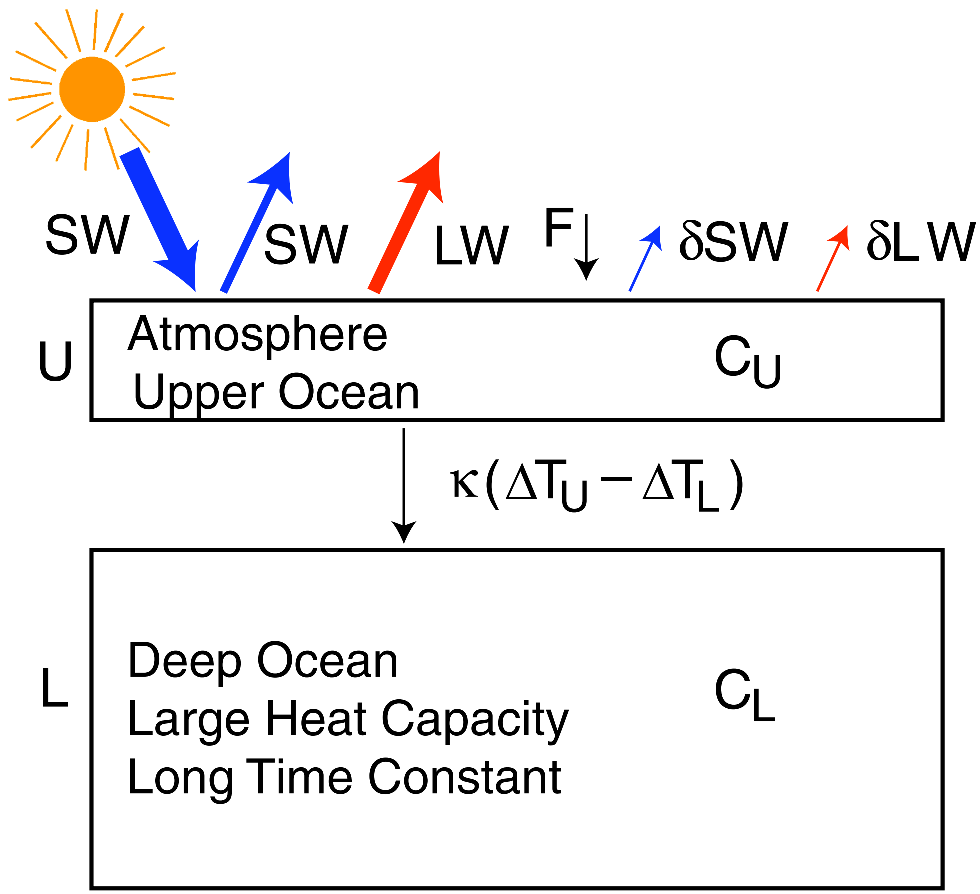
At new steady state (equilibrium) following application of constant forcing F

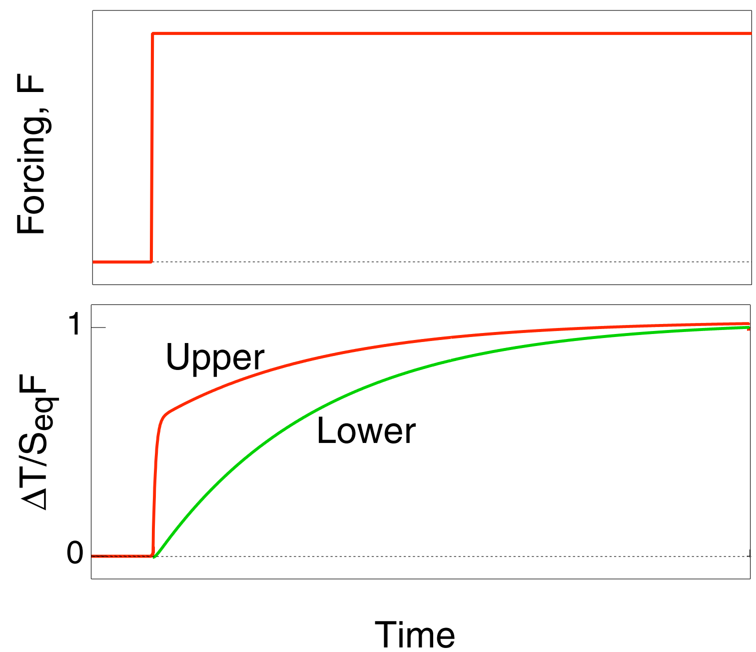
$$N = 0; \quad \lambda \Delta T = F; \quad \boxed{\Delta T = \lambda^{-1} F = S_{\mathrm{eq}} F}$$

S_{eq} = *equilibrium climate sensitivity* = λ^{-1}.

S_{eq} is a geophysical property of Earth's climate system.

Two compartment climate model





PREDECESSORS TO THIS MODEL

Gregory,
Climate Dynamics,
2001

$$c d_\mathrm{u} \frac{\mathrm{d}T_\mathrm{u}}{\mathrm{d}t} = H - k(T_\mathrm{u} - T_\mathrm{l})$$

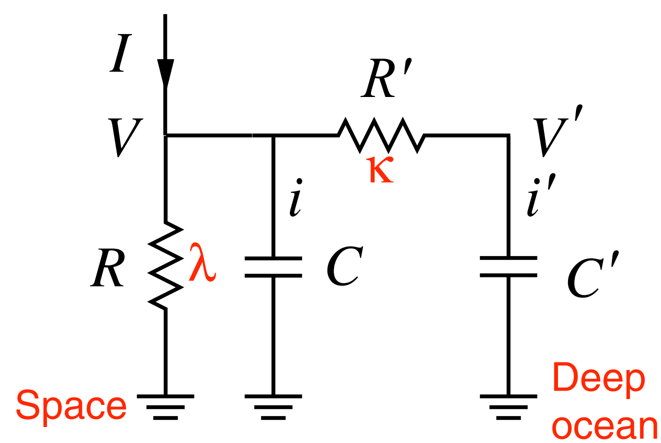
$$c d_\mathrm{l} \frac{\mathrm{d}T_\mathrm{l}}{\mathrm{d}t} = k(T_\mathrm{u} - T_\mathrm{l})$$

Held et al,
J. Climate, 2010

$$c_F \frac{dT}{dt} = \mathcal{F} - \beta T - \gamma(T - T_D)$$

$$c_D \frac{dT_D}{dt} = \gamma(T - T_D)$$

Schwartz,
JGR, 2008



EMPIRICAL DETERMINATION OF COMPARTMENT HEAT CAPACITIES

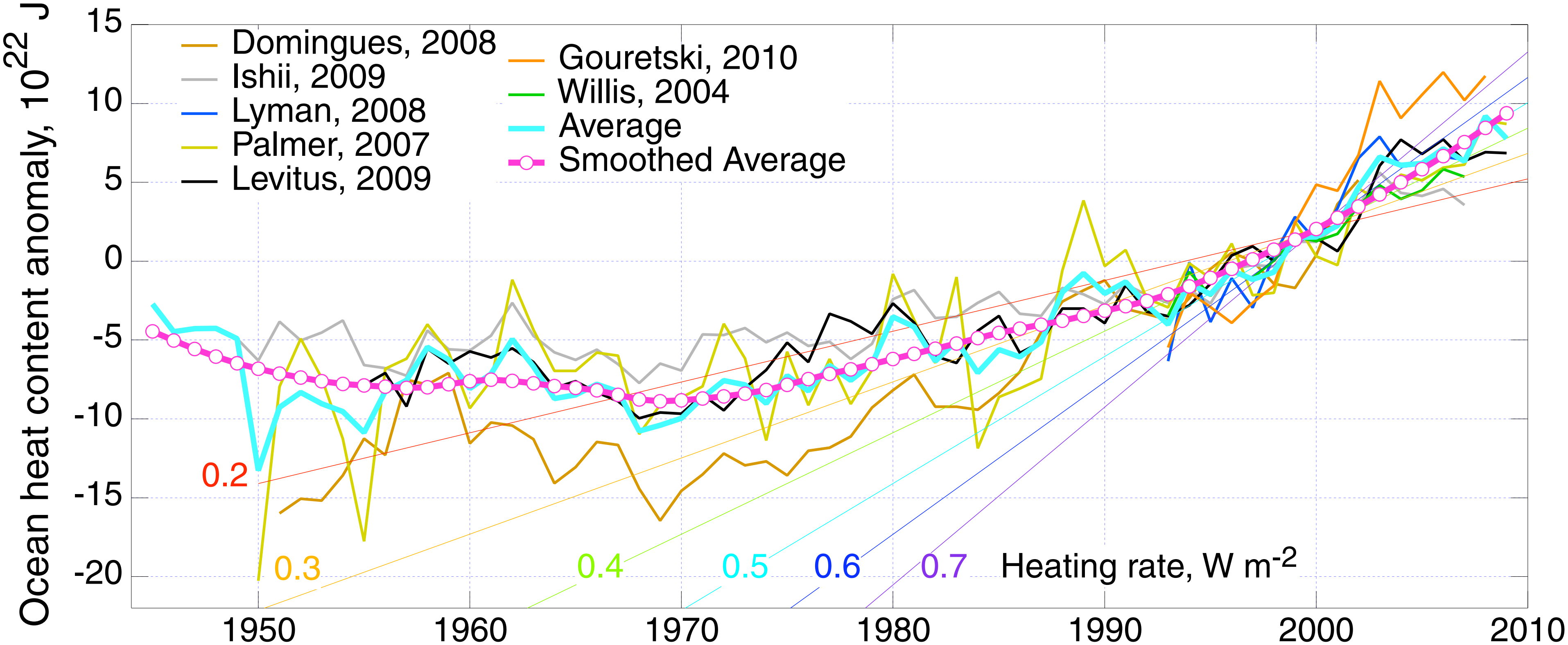
Hypothesis: Planetary heat content increases linearly with surface temperature ΔT.

Plot $H(t)$ vs $\Delta T(t)$; determine C_{U} as slope.

Calculate C_{L} from volume of world ocean.

C_{U} and C_{L} are geophysical properties of Earth's climate system.

Heat content of global ocean



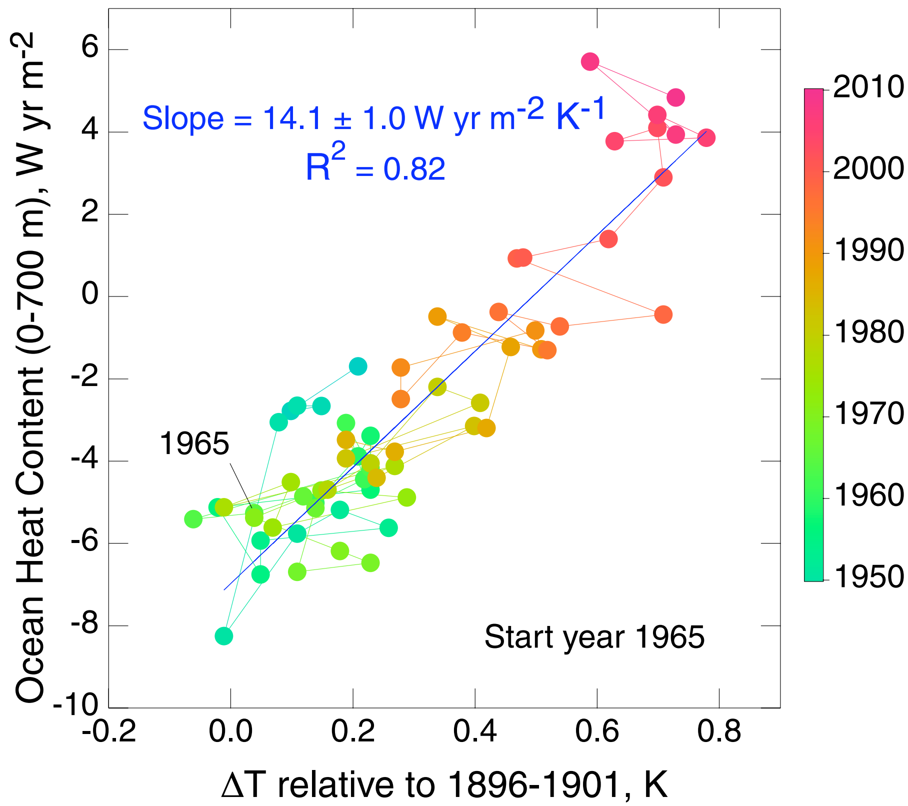
Heat content is from XBT soundings, later Argo robotic buoys.

Uncertainties from representativeness, techniques ...

Smoothed curve is LOWESS fit.

Monotonic increase since about 1970.

World ocean heat content vs temperature anomaly

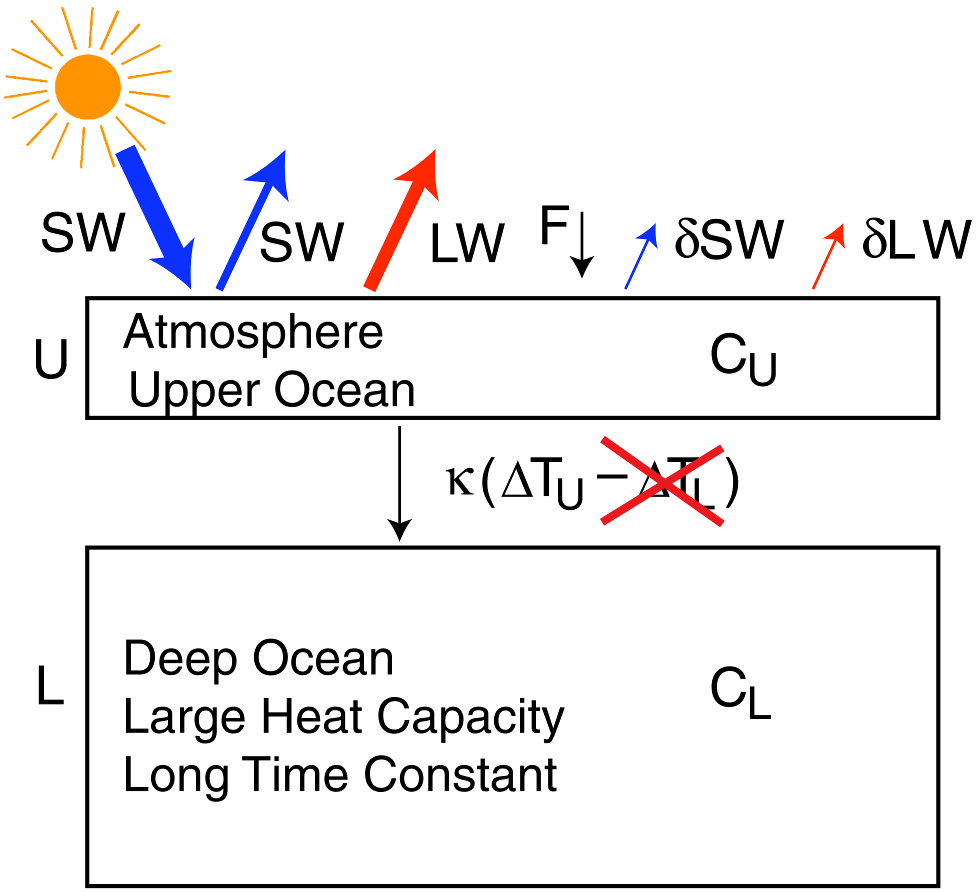


Heat content varies linearly with temperature anomaly.

Heat capacity determined as slope, accounting for additional heat sinks (deep ocean, air, land, ice melting).

Upper compartment heat capacity C_U = 21.8 ± 2.1 W yr m^{-2} K^{-1} (1 σ, based on fit, not systematic errors); equivalent to 170 m of seawater, globally.

Two compartment climate model



EMPIRICAL DETERMINATION OF HEAT EXCHANGE COEFFICIENT

Hypothesis: Planetary heating rate proportional to ΔT

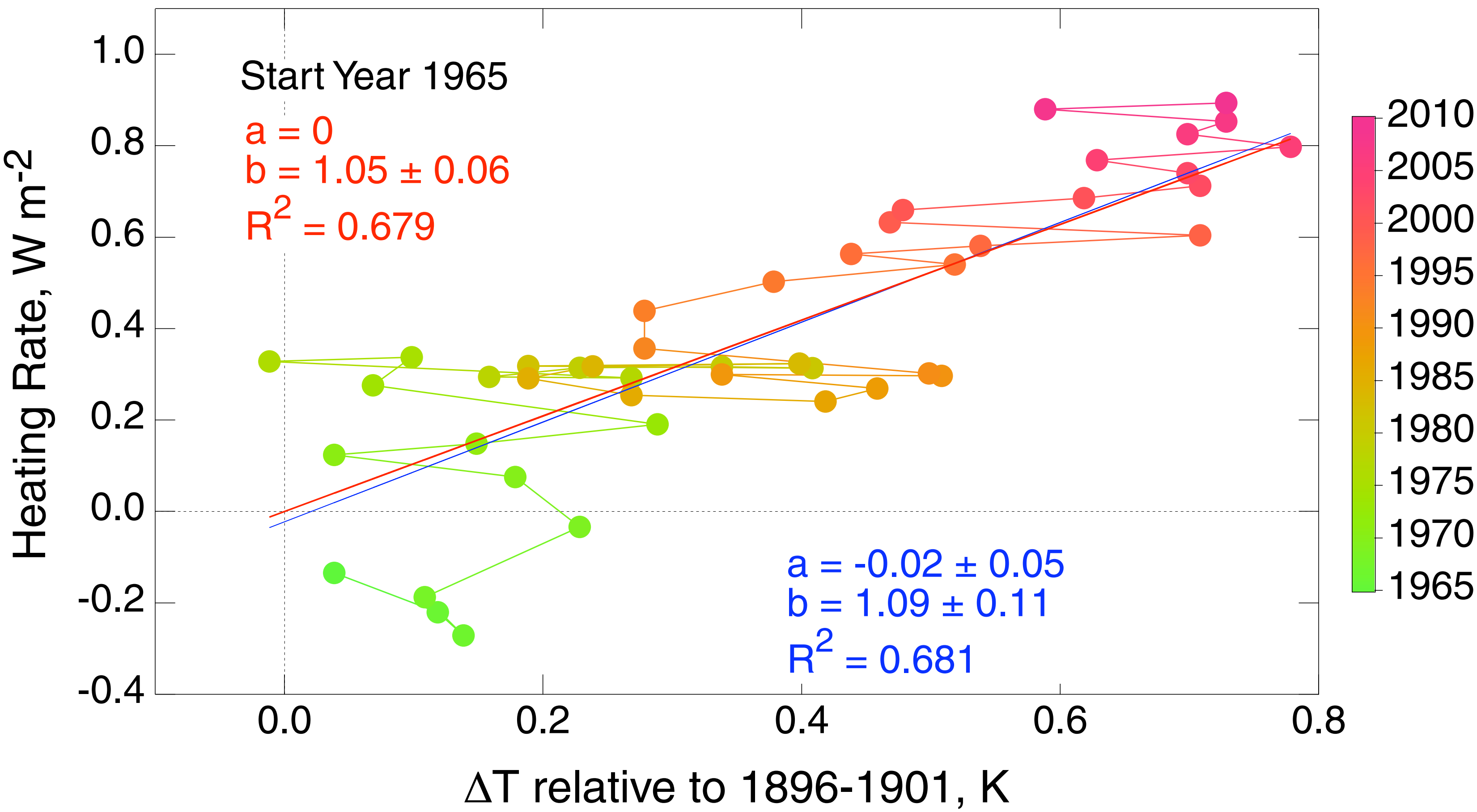
$$N(t) = \kappa \Delta T(t)$$

$\kappa =$ *heat exchange coefficient.*

Plot $N(t)$ vs $\Delta T(t)$; determine κ as slope (with zero origin).

κ is a geophysical property of Earth's climate system.

Global heating rate vs temperature anomaly



Heating rate (time derivative of ocean heat content) is ***linearly proportional*** to temperature anomaly.

Heat exchange coefficient $\kappa = 1.05 \pm 0.06$ W m^{-2} K^{-1} (1σ, based on fit, not systematic errors).

TRANSIENT CLIMATE SENSITIVITY

Assumption: Planetary heating rate proportional to ΔT

$$N(t) = \kappa \Delta T(t)$$

$\kappa =$ *heat exchange coefficient*, a geophysical property of Earth's climate system.

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

$$\boxed{F(t) = (\kappa + \lambda)\Delta T(t);\;\; \Delta T(t) = (\kappa + \lambda)^{-1} F(t) = S_{\mathrm{tr}} F(t)}$$

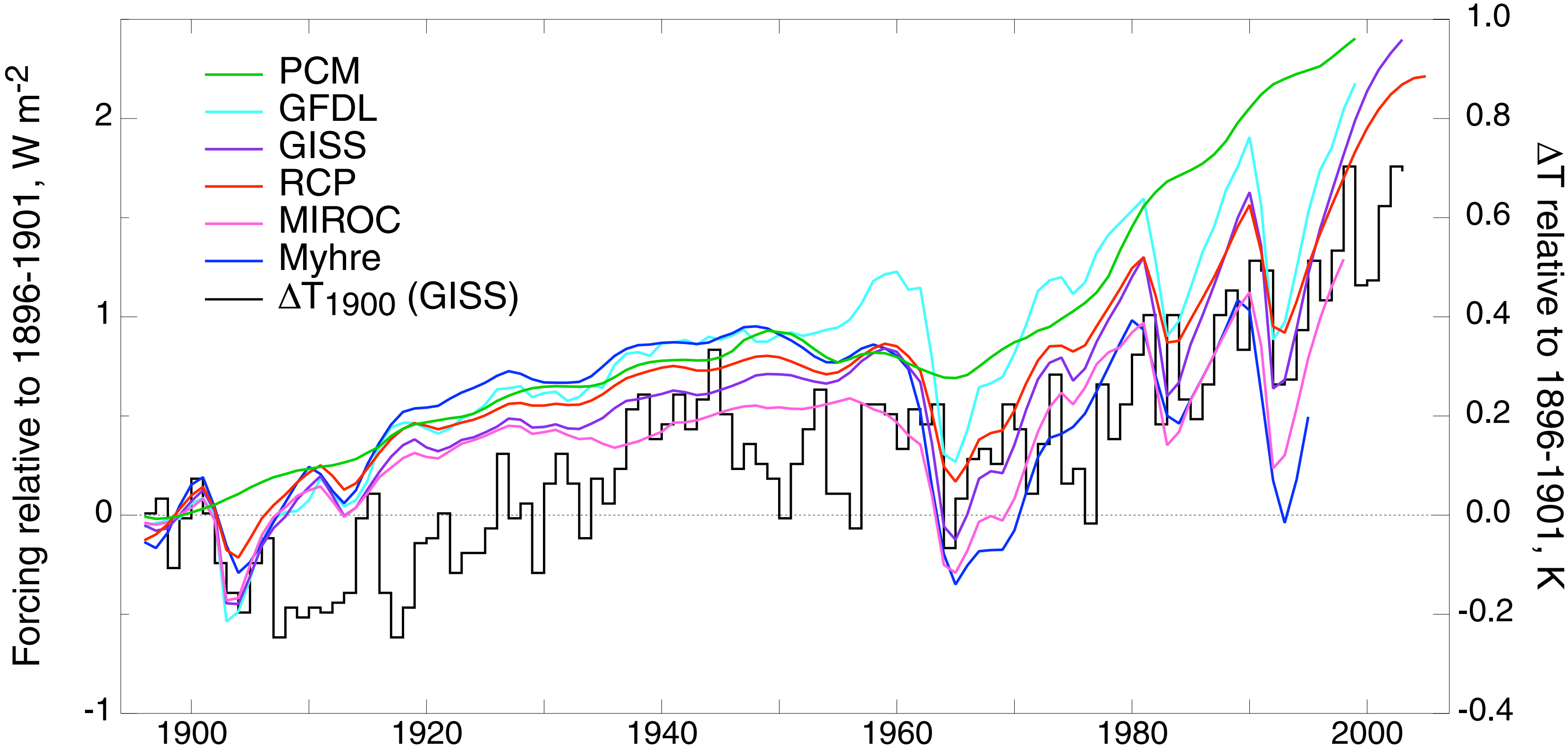
$S_{\mathrm{tr}} =$ *transient climate sensitivity*, $S_{\mathrm{tr}} \equiv (\kappa + \lambda)^{-1}$, a geophysical property of Earth's climate system

Contrast equilibrium sensitivity, $S_{\mathrm{eq}} = \lambda^{-1}$

FORCING DATA SETS EXAMINED IN THIS STUDY

Forcing Data Set	Forcing, 1900-1990, W m^{-2}
PCM, Parallel Climate Model, National Center for Atmospheric Research; Meehl et al., 2003	2.1
GFDL, Geophysical Fluid Dynamics Laboratory; Held et al., 2010	1.9
GISS, Goddard Institute for Space Studies; Hansen et al., 2005	1.6
RCP - Representative Concentration Pathways; Meinshausen et al., 2010	1.6
MIROC, Model for Interdisciplinary Research On Climate; Takemura et al., 2006	1.1
Myhre et al., 2001	1.0

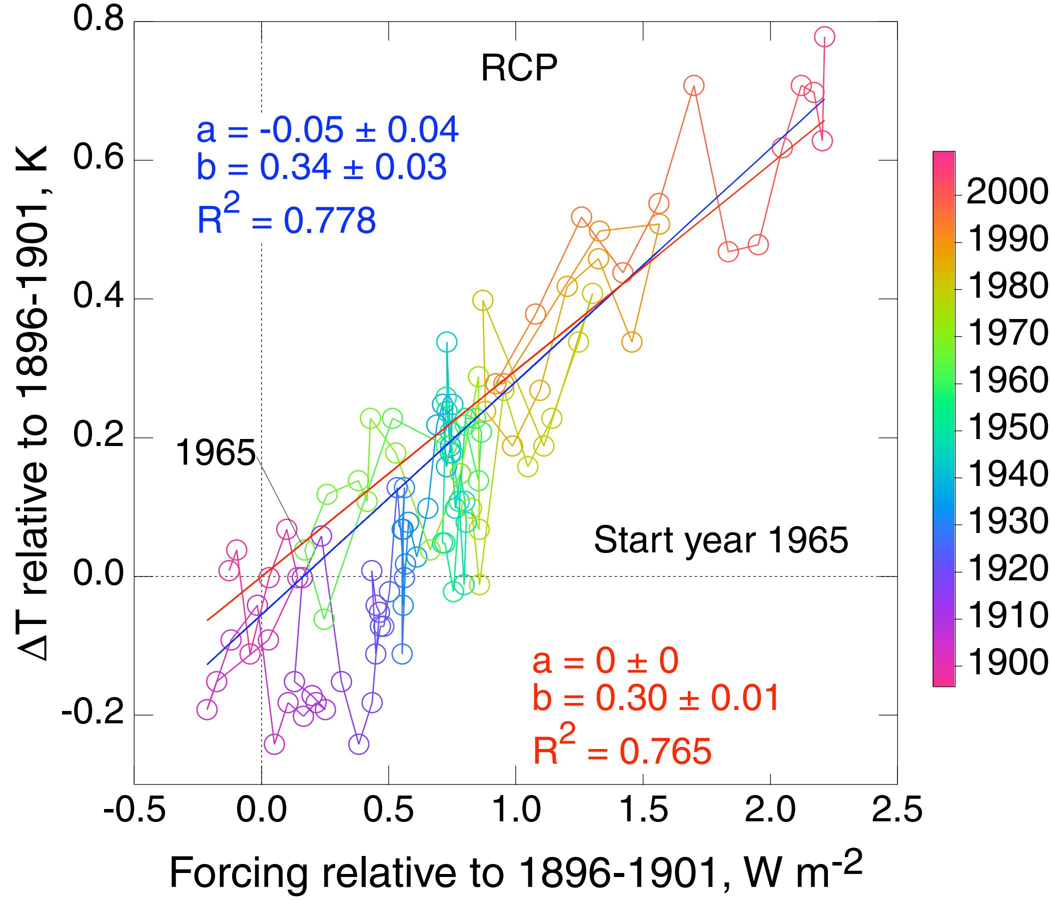
Forcings and temperature anomaly over the twentieth century



Forcings from published studies (convolved with 3-year exponential to smooth out fast fluctuations) are input to the determination of sensitivities.

Forcings and temperature anomaly are more or less coherent.

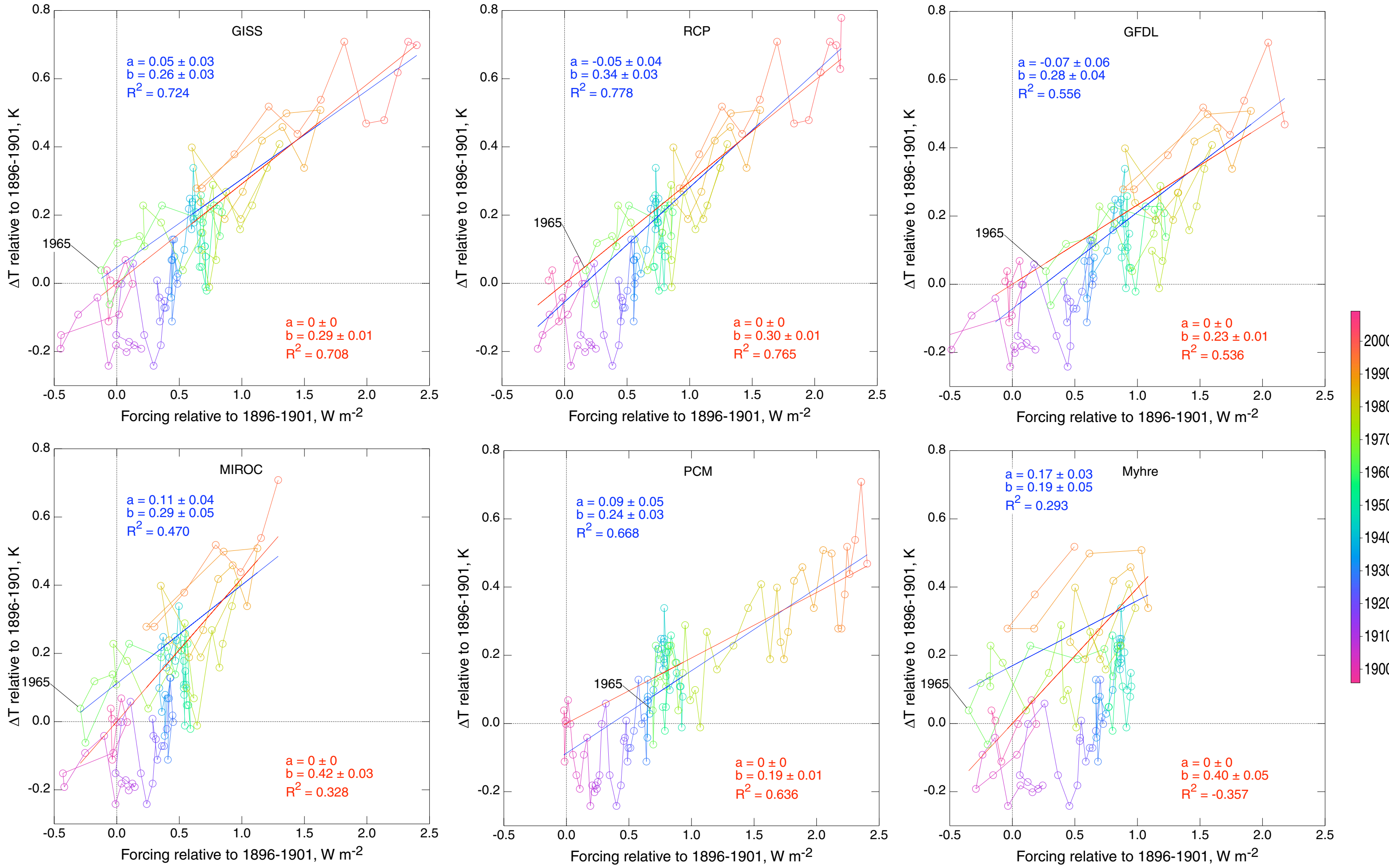
Temperature anomaly vs forcing – RCP forcing dataset



RCP: "Representative Concentration Pathways" – default for IPCC AR5 climate model runs.

ΔT is linearly proportional to forcing, consistent with transient sensitivity model; slope yields ***transient*** sensitivity.

Temperature anomaly vs forcing – 6 forcing datasets



ΔT is ***linearly proportional*** to forcing for most forcing datasets, consistent with model.

Slope yields ***transient*** sensitivity.

Transient sensitivity differs for different forcing datasets.

SUMMARY OF FINDINGS

GEOPHYSICAL QUANTITIES DETERMINED IN THIS STUDY

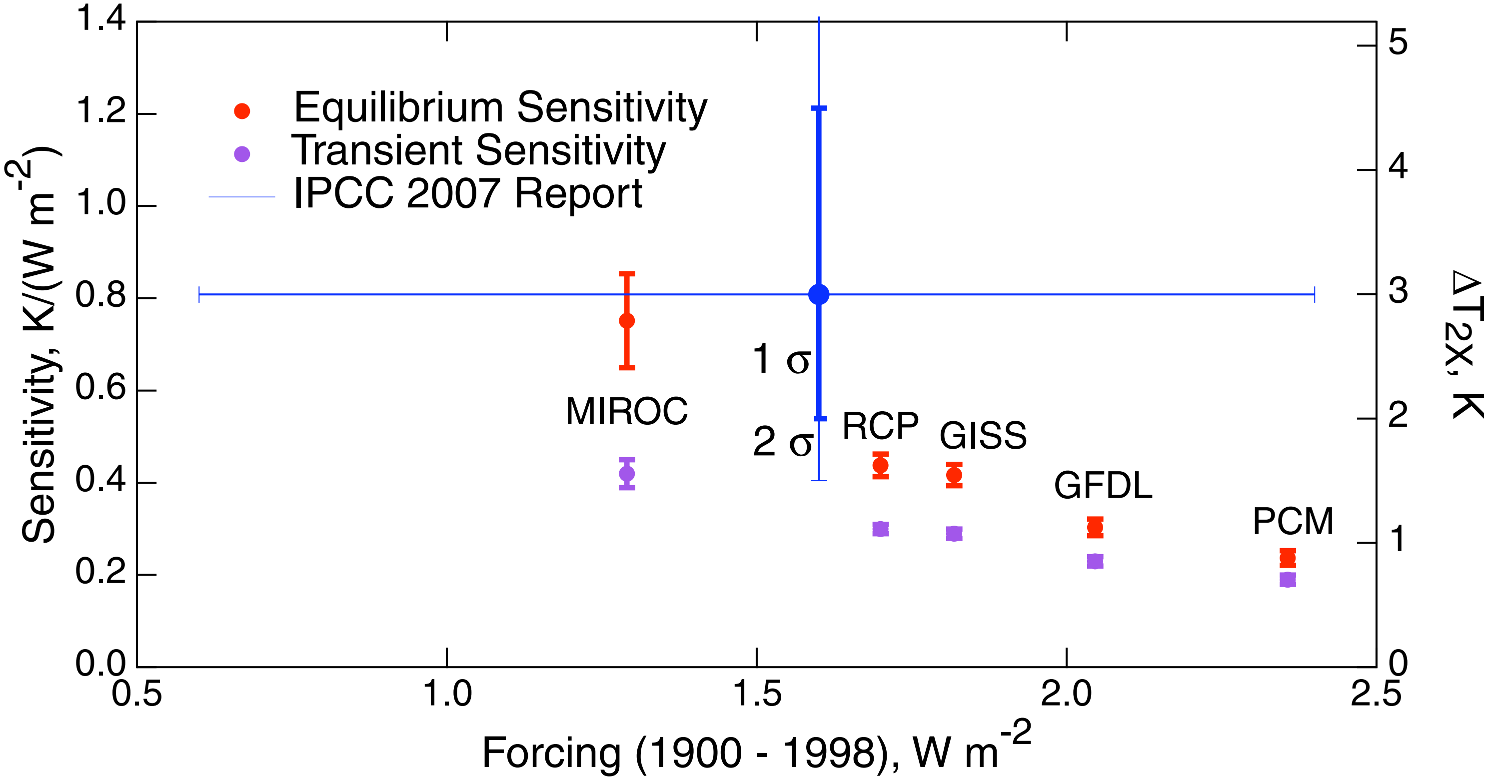
(Independent of Forcing)

Quantity	Unit	Value	σ
κ	W m^{-2} K^{-1}	1.05	0.06
C_{U}	W yr m^{-2} K^{-1}	21.8	2.1
C_{L}	W yr m^{-2} K^{-1}	340	

FORCING-DEPENDENT QUANTITIES DETERMINED IN THIS STUDY

		Forcing Data Set				
Quantity	Unit	PCM	GFDL	GISS	RCP	MIROC
F(1900-1990)	W m^{-2}	2.1	1.9	1.6	1.6	1.1
S_{tr}	K (W m^{-2}) $^{-1}$	0.19	0.23	0.29	0.30	0.42
$\Delta T_{2\times,\,tr}$	K	0.70	0.85	1.08	1.11	1.56
S_{eq}	K (W m^{-2})$^{-1}$	0.24	0.30	0.42	0.44	0.75
$\Delta T_{2\times,\,eq}$	K	0.88	1.12	1.54	1.62	2.78
τ_s	yr	4.1	5.0	6.3	6.5	9.2
τ_l	yr	405	427	466	473	579

Climate sensitivities vs forcing



Equilibrium sensitivities are lower to much lower than IPCC central estimate. Transient sensitivities are even lower.

Inferred transient and equilibrium sensitivities vary inversely with assumed twentieth century forcing.

Determination of sensitivities remains hostage to uncertainty in forcing, due mainly to aerosols.

Response times in two-compartment model

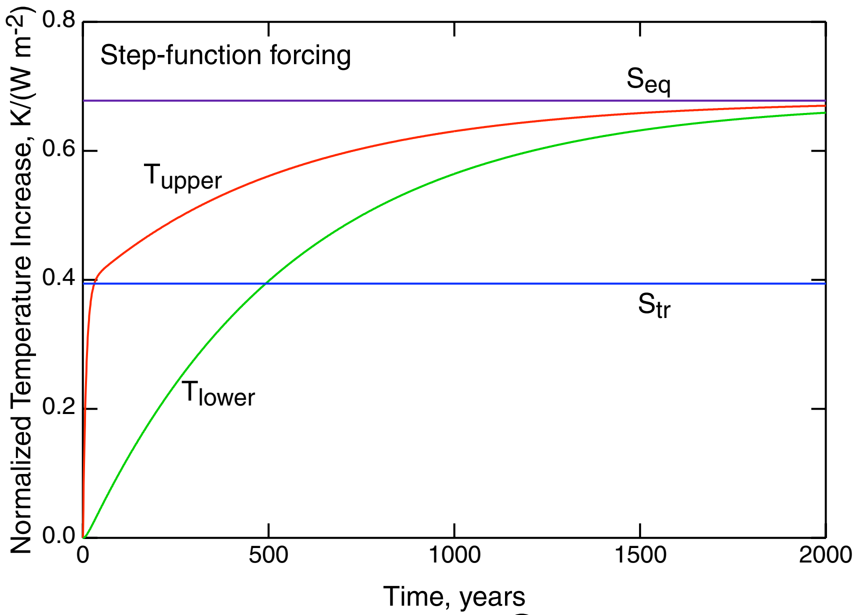
$$\tau_s = \frac{C_U}{\kappa + \lambda} \qquad \tau_1 = C_L\left(\frac{1}{\lambda} + \frac{1}{\kappa}\right)$$

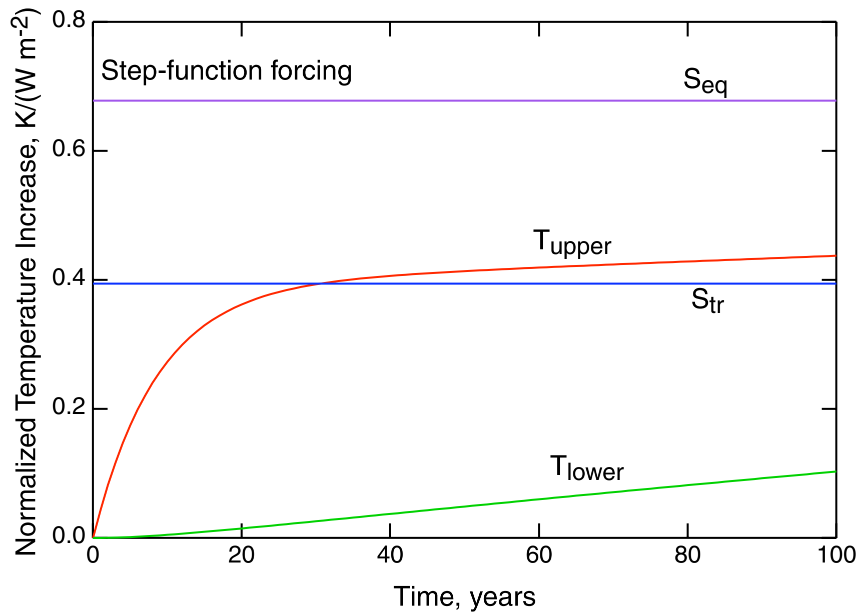
Obtained from eigenvalues, to first order in C_U / C_L.

Time constants can be evaluated from heat capacities and equilibrium and transient sensitivities.

τ_s and τ_1 are geophysical properties of Earth's climate system.

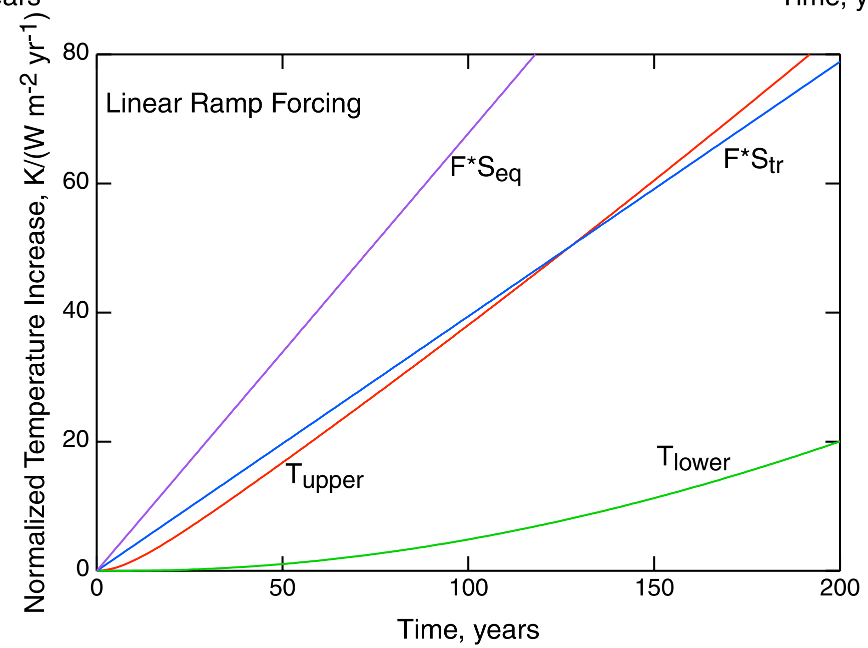
Temperature response to forcings in 2-compartment system





τ_S = 9 yr

τ_l = 550 yr



Transient sensitivity yields good estimate over initial 100-200 years.

PREDECESSORS TO THIS STUDY

Gregory,
Climate Dynamics,
2001

$$cd_u \frac{dT_u}{dt} = H - k(T_u - T_l)$$

$$cd_l \frac{dT_l}{dt} = k(T_u - T_l)$$

$\kappa = 1.6\ (\mathrm{W\ m^{-2}})/\mathrm{K}$

$\tau_s = 12$ yr

Held et al,
J. Climate, 2010

$$c_F \frac{dT}{dt} = \mathcal{F} - \beta T - \gamma(T - T_D)$$

$$c_D \frac{dT_D}{dt} = \gamma(T - T_D)$$

$\kappa = 1.3\ (\mathrm{W\ m^{-2}})/\mathrm{K}$

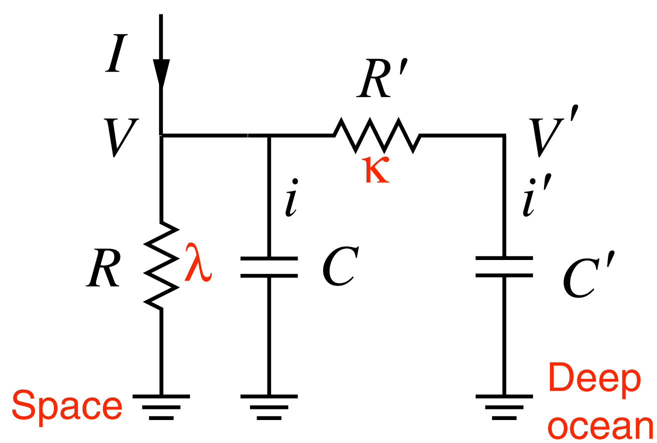
$\Delta T_{2\times,\mathrm{eq}} = 3.4$ K

$\Delta T_{2\times,\mathrm{tr}} = 1.5$ K

$\tau_s = 4$ yr

$\tau_1 =$ "recalcitrant"

This study



$\kappa = 1.1\ (\mathrm{W\ m^{-2}})/\mathrm{K}$

$\Delta T_{2\times,\mathrm{tr}} = 0.7 - 1.6$ K

$\Delta T_{2\times,\mathrm{eq}} = 0.9 - 2.8$ K

$\tau_s = 5 - 9$ yr

$\tau_1 = 400 - 600$ yr

SUMMARY & CONCLUSIONS (1)

The ***effective heat capacity*** of the upper, short-time-constant compartment of the climate system, accounting for other heat sinks, is found to be 21.8 ± 2.1 W yr m^{-2} K^{-1} (1 σ).

The ***rate of planetary heat uptake is found to be proportional to the increase in global temperature*** relative to the beginning of the twentieth century with ***heat exchange coefficient*** 1.05 ± 0.06 W m^{-2} K^{-1} (1 σ).

Transient and equilibrium climate sensitivity were examined for six published forcing data sets having twentieth century forcing ranging from 1.1 to 2.1 W m^{-2}, spanning much of the range encompassed by the 2007 IPCC assessment.

SUMMARY & CONCLUSIONS (2)

For five of the six forcing data sets a rather robust linear proportionality is observed between the observed change in global temperature and the forcing, allowing transient sensitivity to be determined as the slope.

Equilibrium sensitivities range from 0.24 to 0.75 K $(W\ m^{-2})^{-1}$ (CO_2 doubling temperature 0.88 to 2.75 K), ***less to well less than the IPCC central value*** and estimated uncertainty range for this sensitivity.

Transient sensitivities are less to well less than equilibrium sensitivities.

Values of sensitivity are strongly anticorrelated with the forcing used to determine sensitivity.

SUMMARY & CONCLUSIONS (3)

Improved empirical determination of transient or equilibrium climate sensitivity, and also determination by climate models, ***requires uncertainty in aerosol forcing to be greatly reduced***.

Values of the time constant characterizing the response of the ***upper ocean*** component of the climate system to perturbations range from ***4 to 9 years***.

Transient sensitivity would seem to be more important than equilibrium sensitivity in decisions regarding future CO_2 ***emissions.***