EARTH'S TRANSIENT AND EQUILIBRIUM CLIMATE SENSITIVITIES

HOW MUCH CAN WE LEARN FROM OBSERVATIONS?

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

EQUILIBRIUM CLIMATE SENSITIVITY

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

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

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

Sensitivity is commonly expressed as "CO_2 doubling temperature"

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

where $F_{2\times}$ is the CO_2 doubling forcing, *ca*. 3.7 W m^{-2}.

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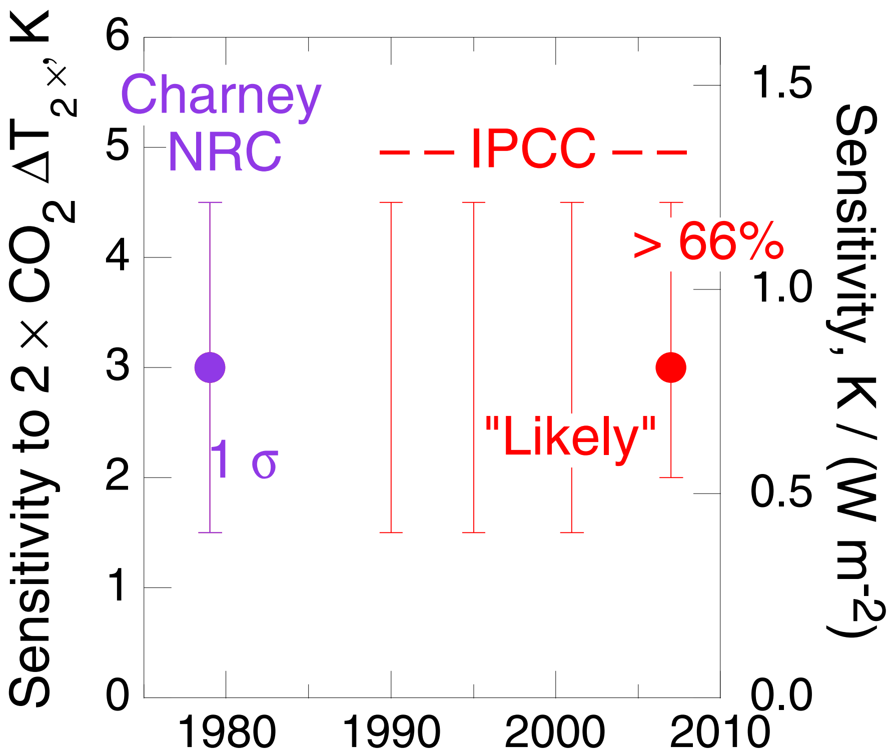
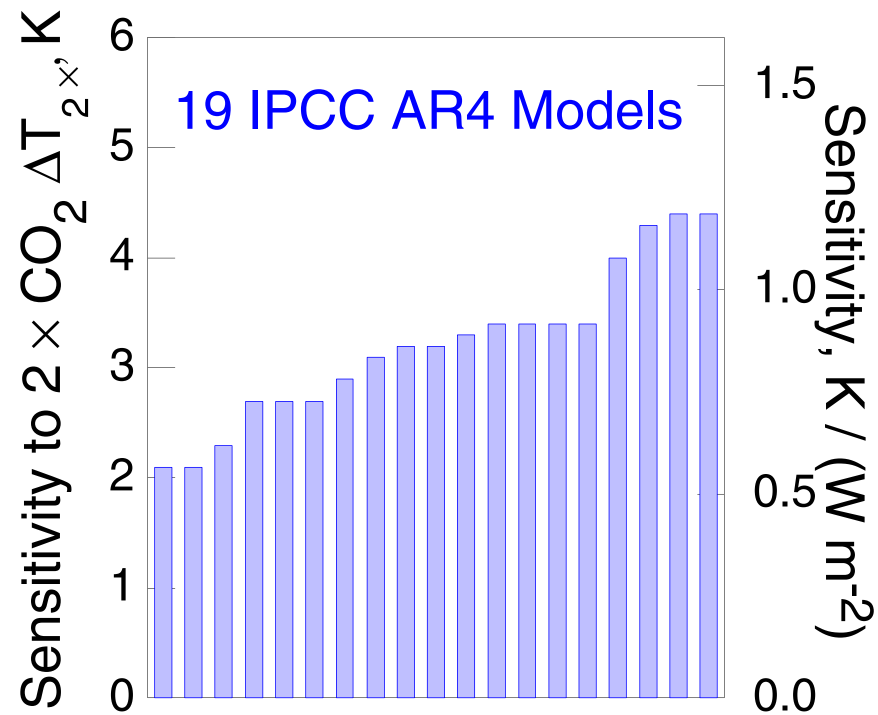
ESTIMATES OF EARTH'S CLIMATE SENSITIVITY AND ASSOCIATED UNCERTAINTY

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.

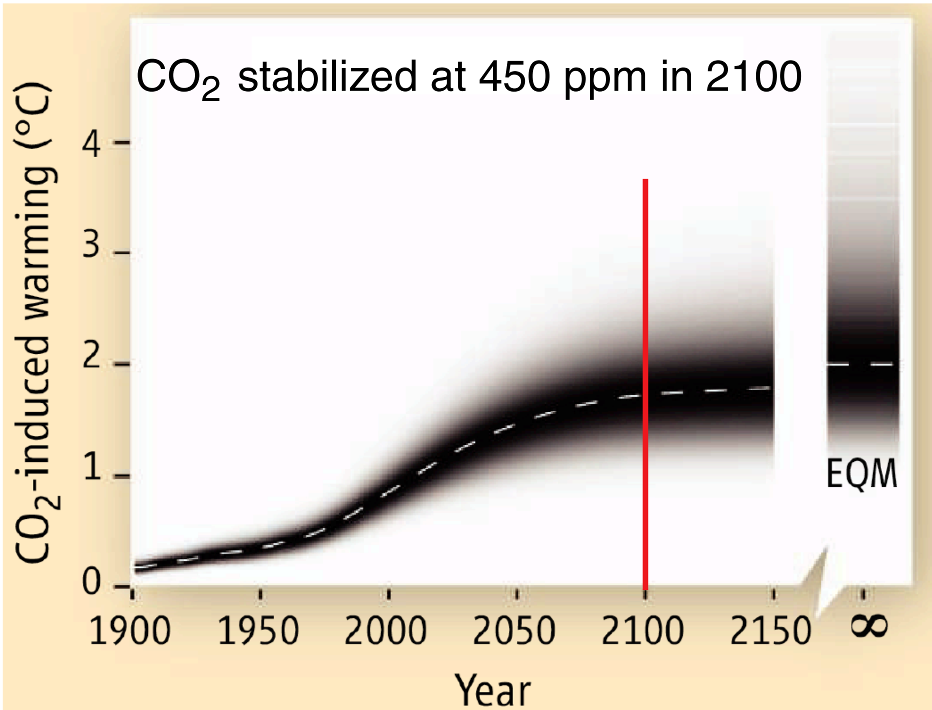
26 OCTOBER 2007 VOL 318 **SCIENCE** www.sciencemag.org

ATMOSPHERE

Call Off the Quest

Myles R. Allen and David J. Frame

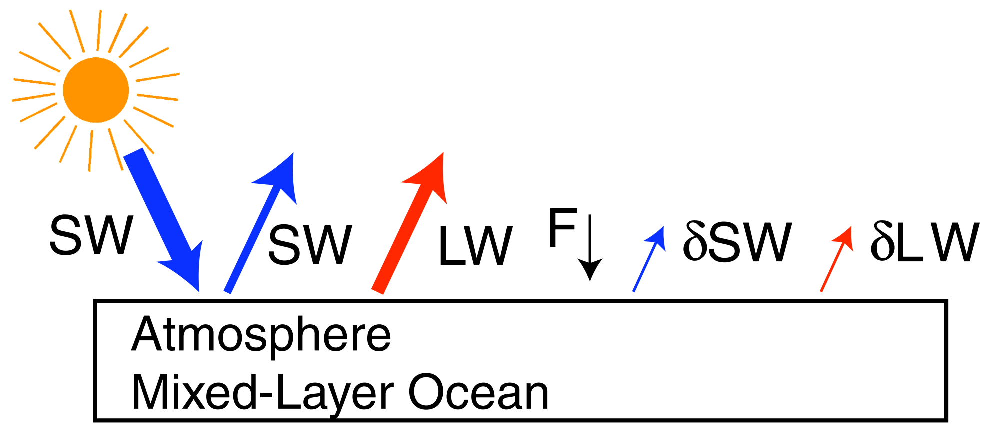
Knowledge of the long-term response of Earth's climate to a doubling of atmospheric carbon doixide may be less useful for policy-makers than commonly assumed.



“ An upper bound on the climate sensitivity has become the holy grail of climate research.... It is inherently hard to find. It promises lasting fame and happiness to the finder, but it may not exist and turns out not to be very useful if you do find it. Time to call off the quest.

ENERGY BALANCE MODEL

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:

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

Initially after onset of forcing

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

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

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

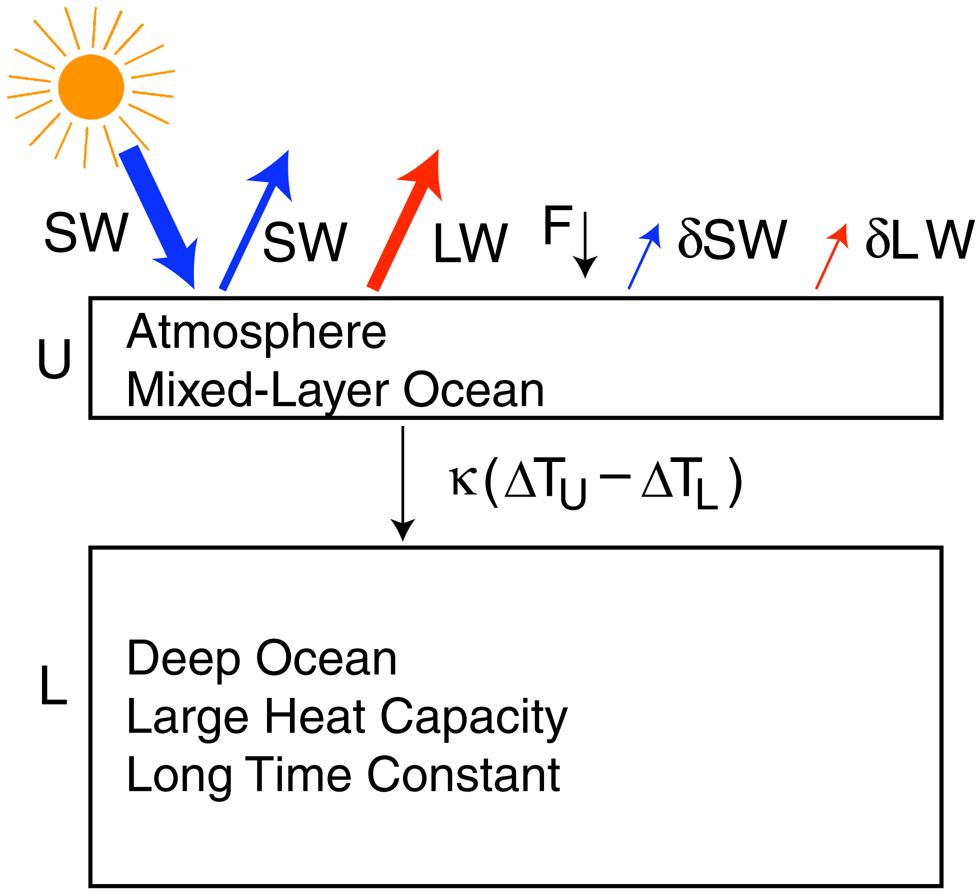
At new steady state (equilibrium) following application of constant forcing F

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

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

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

Two compartment climate model



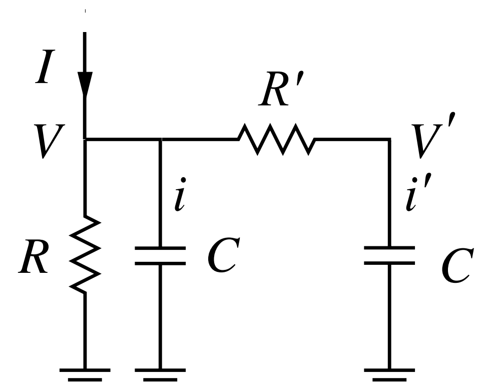
PREDECESSORS TO THIS MODEL

Gregory,
Climate Dynamics,
2001

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

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

Schwartz,
JGR, 2008

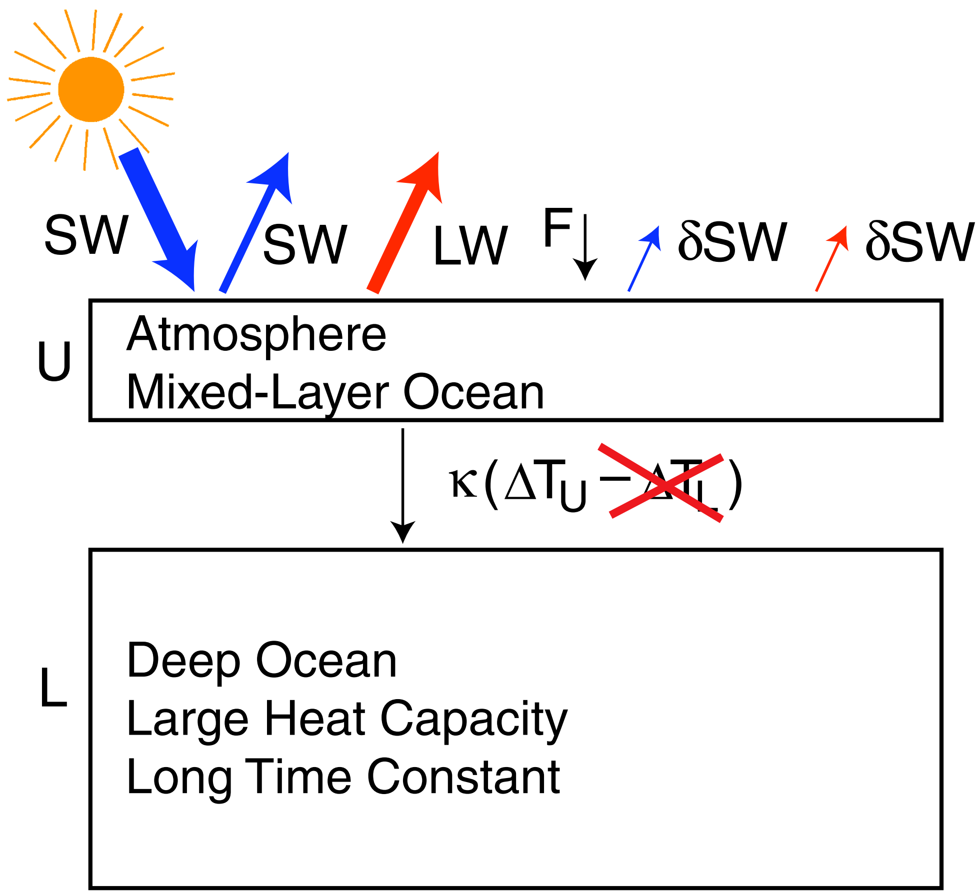


Held et al,
J. Climate, 2010

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

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

Two compartment climate model



TRANSIENT CLIMATE SENSITIVITY

Hypothesis: Planetary heating rate proportional to ΔT

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

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

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

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

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

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

EMPIRICAL DETERMINATION OF HEAT EXCHANGE COEFFICIENT

Hypothesis: Planetary heating rate proportional to ΔT

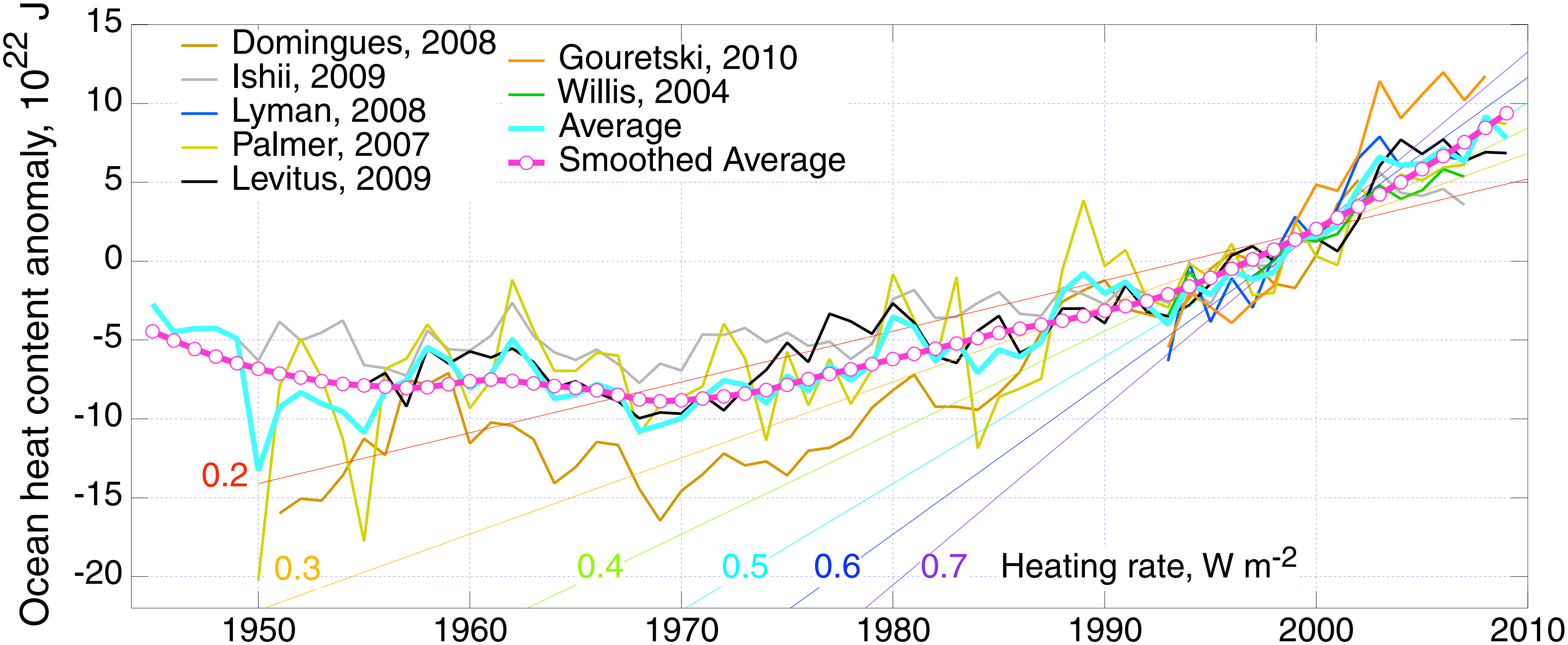
$$N(t) = \kappa \Delta T(t)$$

$\kappa =$ *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.

Heat content of global ocean



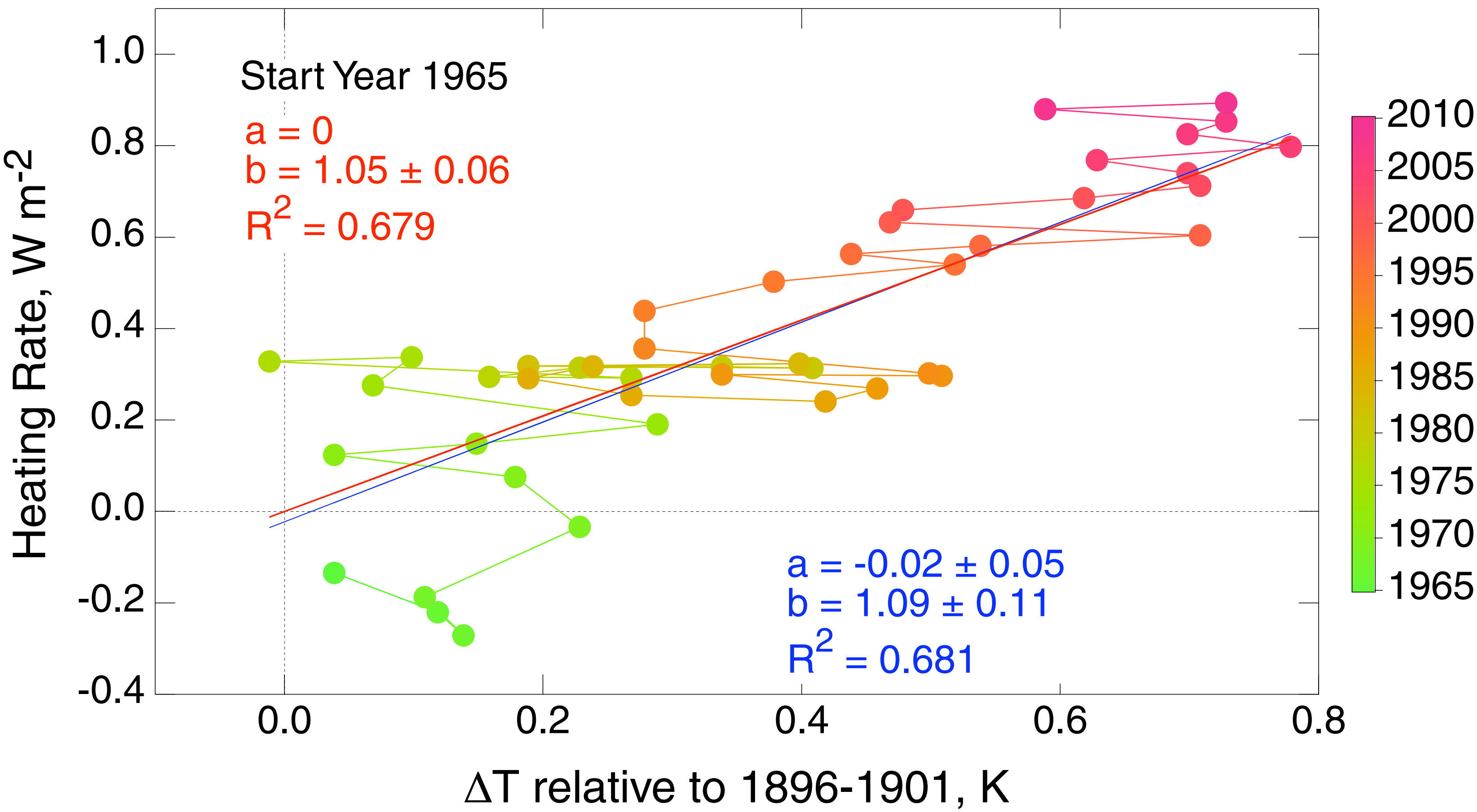
Heat content is from XBT soundings, later Argo robotic buoys.

Uncertainties from representativeness, techniques ...

Smoothed curve is LOWESS fit.

Monotonic increase since about 1970.

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).

Response times in two-compartment model

$$\tau_{\mathrm{s}} = \frac{C_{\mathrm{U}}}{\kappa + \lambda} \qquad \tau_{\mathrm{l}} = C_{\mathrm{L}}\left(\frac{1}{\lambda} + \frac{1}{\kappa}\right)$$

Obtained from eigenvalues, to first order in $C_{\mathrm{U}} / C_{\mathrm{L}}$.

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

τ_{s} and τ_{l} are geophysical properties of Earth's climate system.

EMPIRICAL DETERMINATION OF COMPARTMENT HEAT CAPACITIES

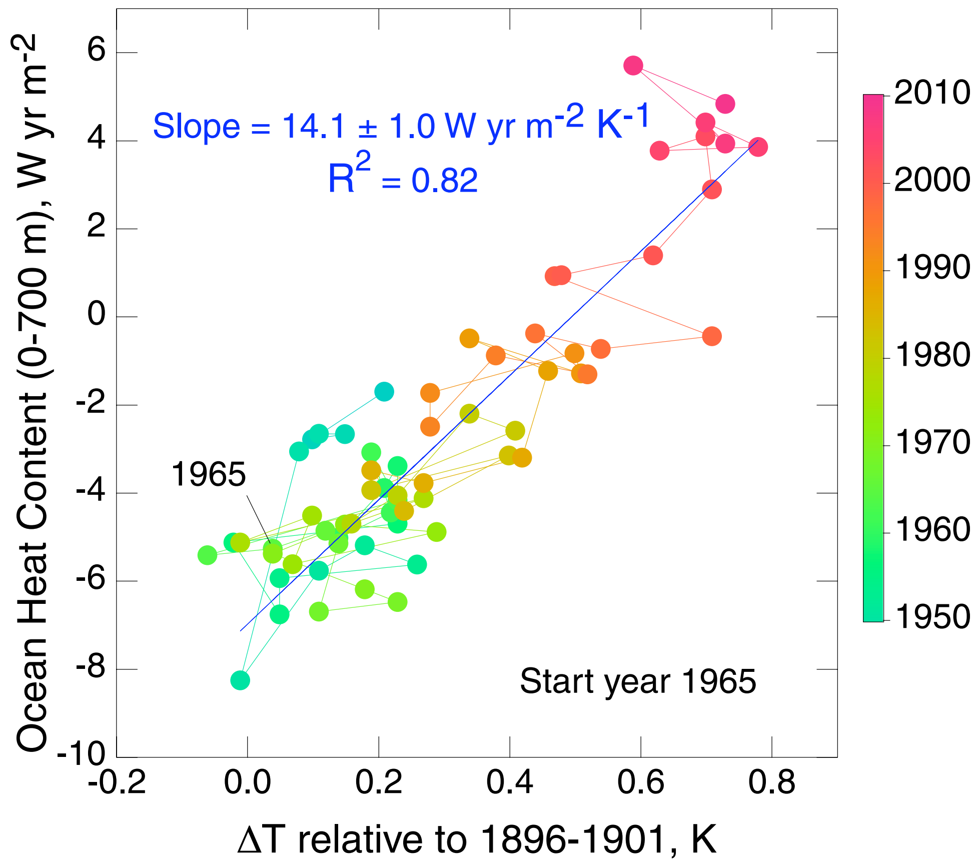
Hypothesis: Planetary heat content increases linearly with surface temperature ΔT.

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.

World ocean heat content vs temperature anomaly



Heat content varies linearly with temperature.

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

Heat capacity of upper compartment $C_U = 21.8 \pm 2.1$ W yr m^{-2} K^{-1} (1 σ, based on fit, not systematic errors).

(170 m of ocean water, globally)

EMPIRICAL DETERMINATION OF TRANSIENT CLIMATE SENSITIVITY

Hypothesis: ΔT proportional to forcing F

$$\Delta T(t) = S_{tr} F(t)$$

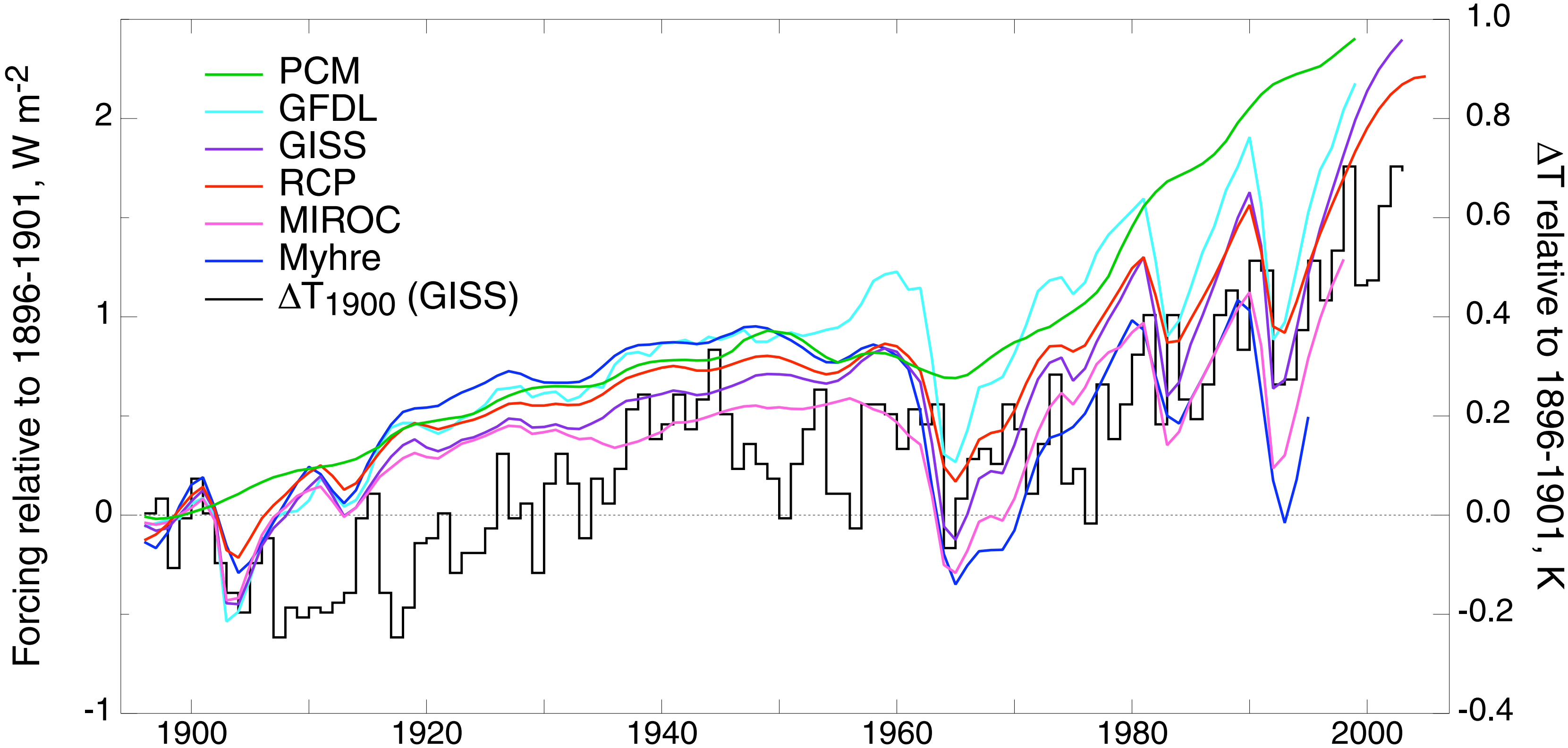
Plot $\Delta T(t)$ vs $F(t)$; determine S_{tr} as slope (with zero origin).

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

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

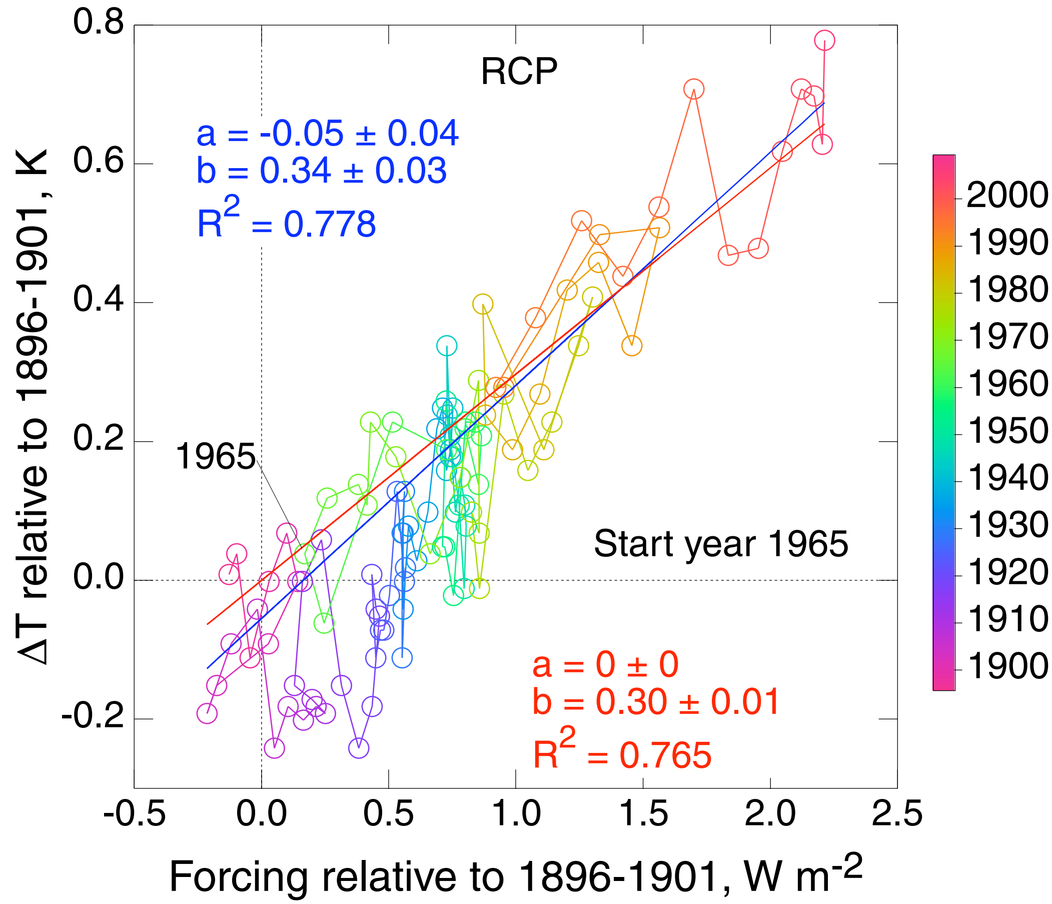
Forcings and temperature anomaly over the twentieth century



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.

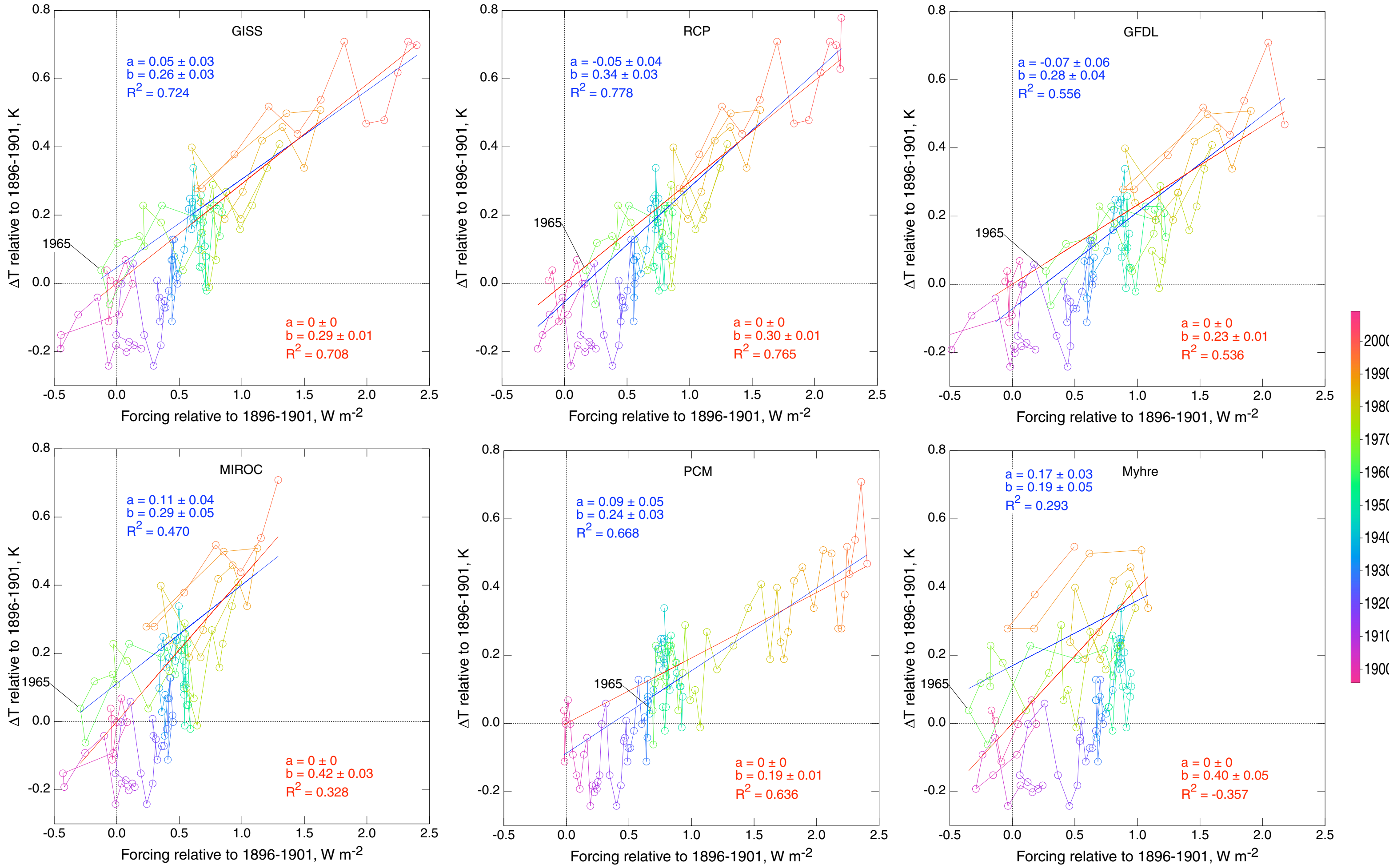
Temperature anomaly vs forcing – RCP forcing dataset



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

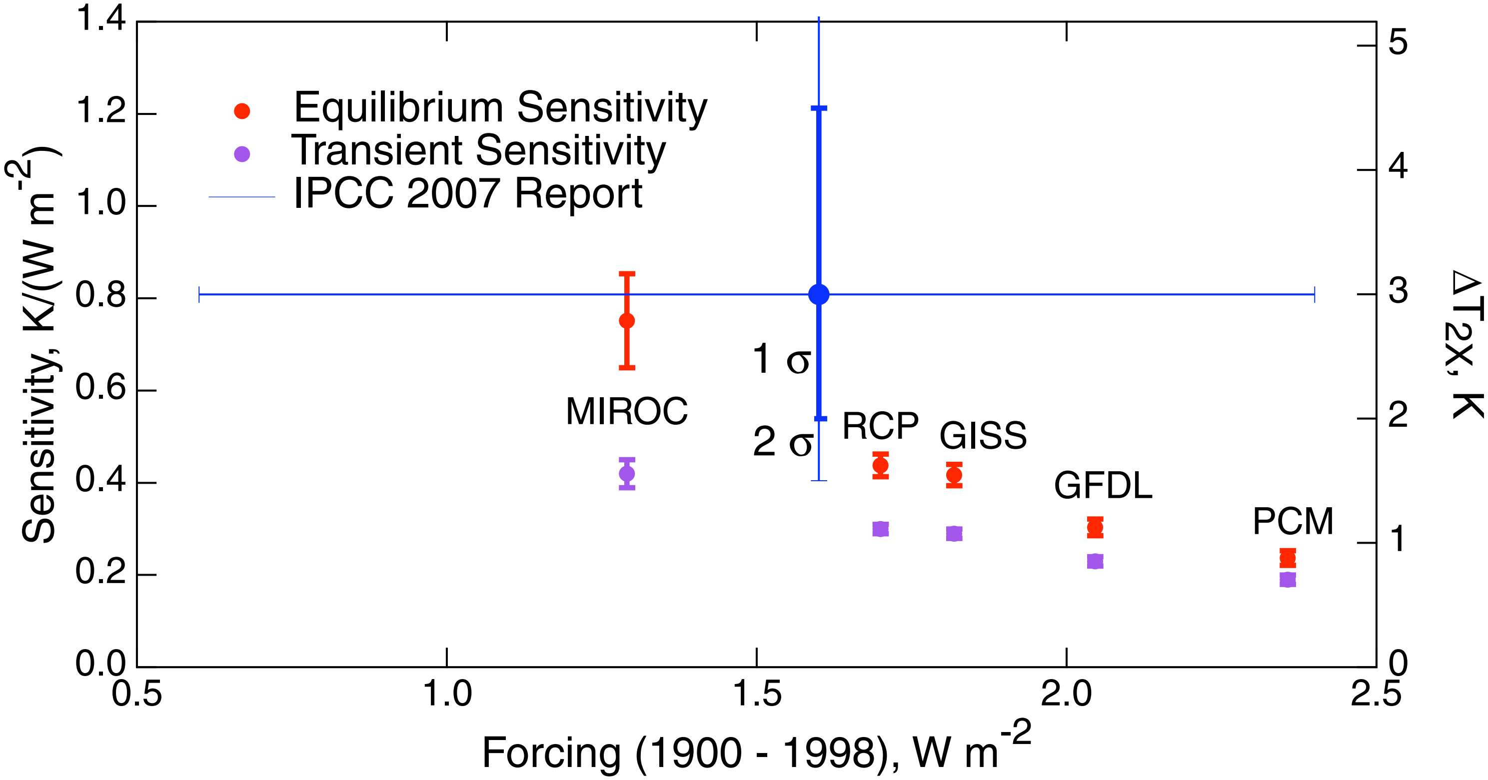
GEOPHYSICAL QUANTITIES DETERMINED IN THIS STUDY

Quantity	Unit	Value	σ
C_U	W yr m^{-2} K^{-1}	21.8	2.1
κ	W m^{-2} K^{-1}	1.05	0.06

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_{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
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
τ_s	yr	4.1	5.0	6.3	6.5	9.2
τ_l	yr	405	427	466	473	579
ΔT_{commit}	K	0.87	0.92	1.01	1.02	1.25
f_{obs}		0.80	0.76	0.70	0.69	0.56

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.

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 $(\text{W m}^{-2})^{-1}$ (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***.

Time constant for equilibration of the ***deep ocean*** is about ***500 years***.

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