EARTH'S TRANSIENT CLIMATE SENSITIVITY EVALUATED FROM AR6 ESTIMATES OF TOTAL FORCING AND OBSERVED TIME SERIES OF GLOBAL TEMPERATURE CHANGE

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MOTIVATION

Earth's climate sensitivity is a key property of Earth's climate system governing interpretation of climate change thus far over the Anthropocene and projections of future climate change in response to prospective changes in emissions and forcings.

Earth's climate sensitivity is ***highly uncertain***; narrowing uncertainty of this sensitivity is a "holy grail" of climate research.

Earth's climate sensitivity is usefully distinguished into two related quantities, transient sensitivity and so-called equilibrium sensitivity*.

Equilibrium sensitivity characterizes long-term, steady-state change in global temperature in response to sustained forcing and takes place only on time scale of millennia.

Transient sensitivity characterizes short-term near-steady-state change in global temperature in response to sustained forcing that takes place on a time scale of 5 or 10 years.

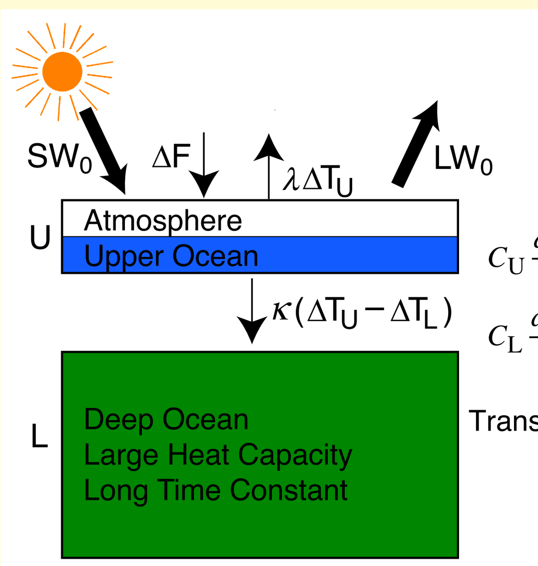
Consequently transient sensitivity is much more pertinent to climate change on the decadal to centennial time scale.

This study provides estimates of transient climate sensitivity based on observed increase in global surface temperature and current (IPCC AR6) estimates of global radiative forcing.

* "Equilibrium sensitivity" is a misnomer. An equilibrium state requires equal and opposite fluxes on all paths; because Earth's climate system is characterized by shortwave in, longwave out, it can never be at equilibrium; at best it can be at a steady state.

TWO-COMPARTMENT CLIMATE MODEL

Relations between energy transfer coefficients and sensitivities



Energy transport equations

$$C_U \frac{dT_U}{dt} = \Delta F - \lambda \Delta T_U - \kappa(\Delta T_U - \Delta T_L)$$

$$C_L \frac{dT_L}{dt} = \kappa(\Delta T_U - \Delta T_L)$$

Transient and equilibrium sensitivities

$$S_{tr} = (\lambda + \kappa)^{-1}$$

$$S_{eq} = \lambda^{-1}$$

APPROACH

IPCC AR6 presents time series of total forcing over the industrial period. Three time series: best estimate and 5% and 95% confidence limits, taking into account uncertainties in forcing, due mainly to uncertainty in aerosol forcing.

Regress annual temperature anomaly (here from GISS) against forcing for the three forcing time series (5%, best, and 95%, denoted low, best, high).

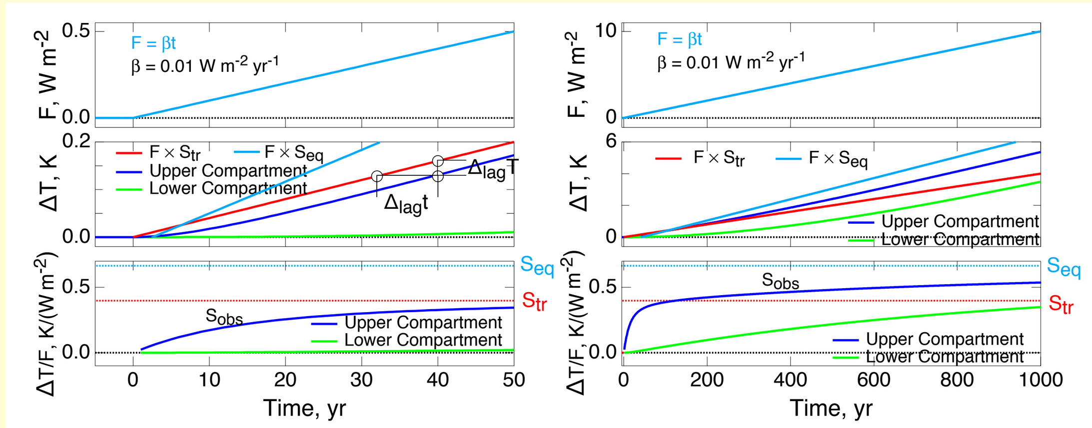
Transient sensitivity is taken as regression slope, neglecting time lags, which are minimal.

Plot time series of temperature change and forcing on same figures, adjusting axes by the regression slope, and compare.

TRANSIENT VS EQUILIBRIUM RESPONSE

Response to ramped forcing as analytical model

Time constant of upper compartment 8 yr



Top panels, ramped forcing, cyan.

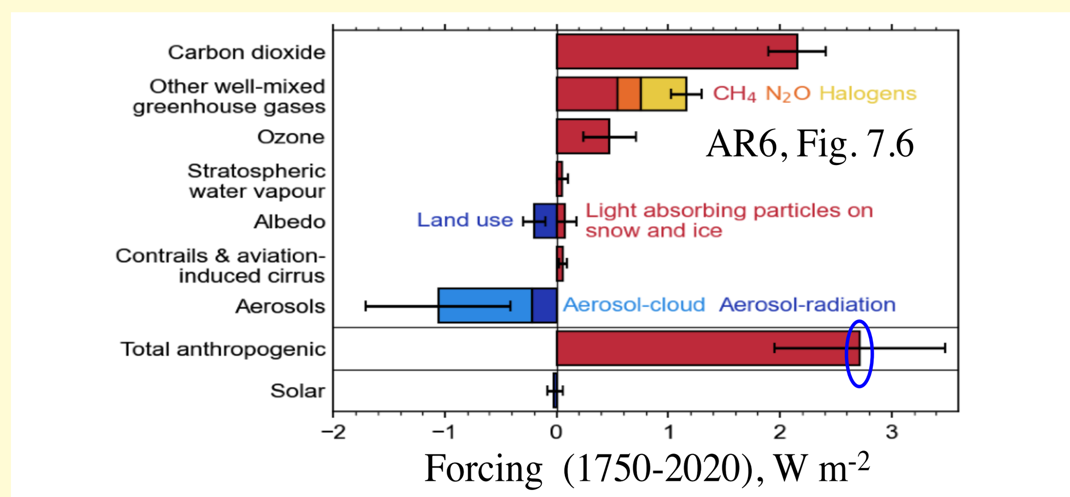
Middle panels, temperature response. Cyan is equilibrium response with no lag, $\Delta T_{eq} = F \times S_{eq}$. Red is transient response with no lag, $\Delta T_{tr} = F \times S_{tr}$. Blue is actual response, slight lag in time ($\Delta_{lag}t$) or temperature ($\Delta_{lag}T$); $\Delta_{lag}T = S_{tr} \times dF/dt \times \Delta_{lag}t$. Green is deep ocean response (large lag).

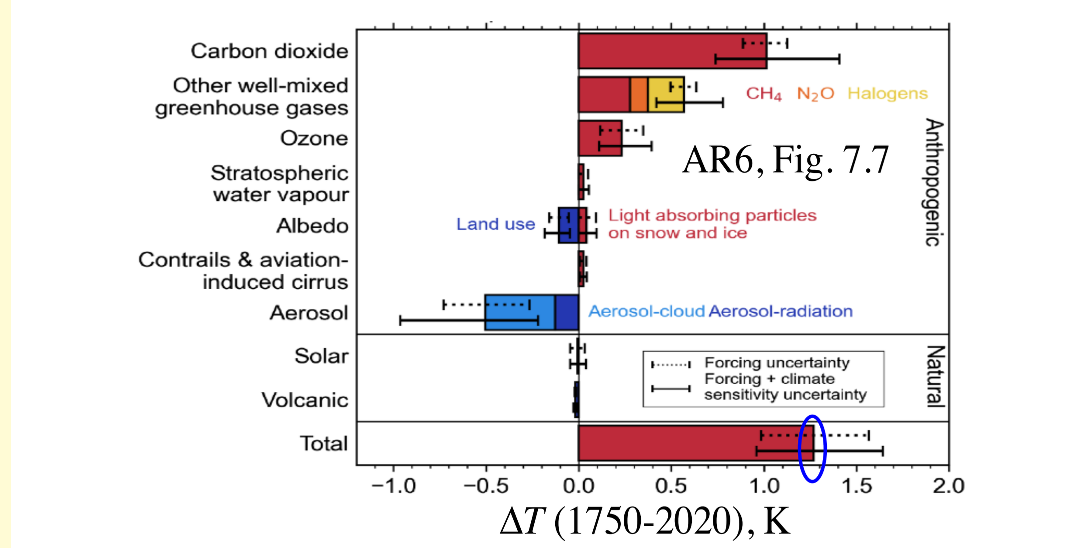
Bottom panels, observed transient sensitivity ($S_{obs} = \Delta T_u/F$) blue, and similarly for lower compartment, green. For ramped forcing even at time as short as 40 years, $S_{obs}/S_{tr} \approx 0.85$ and at 300 years ≈ 1.15.

Observed transient sensitivity provides an accurate measure of actual transient sensitivity over a wide time range.

Equilibrium sensitivity is largely irrelevant on the decadal to centennial time scale.

MODELED FORCING, MODELED TEMP CHANGE





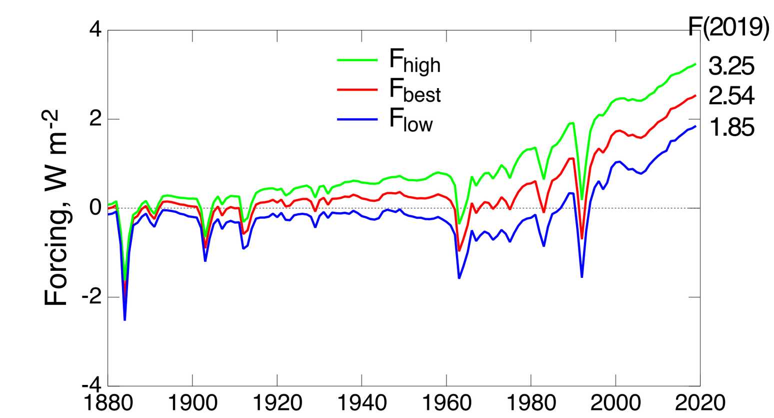
Temperature change, ***calculated with two-layer emulator***, 1.28 K.

Forcing, 2.65 W m^{-2}.

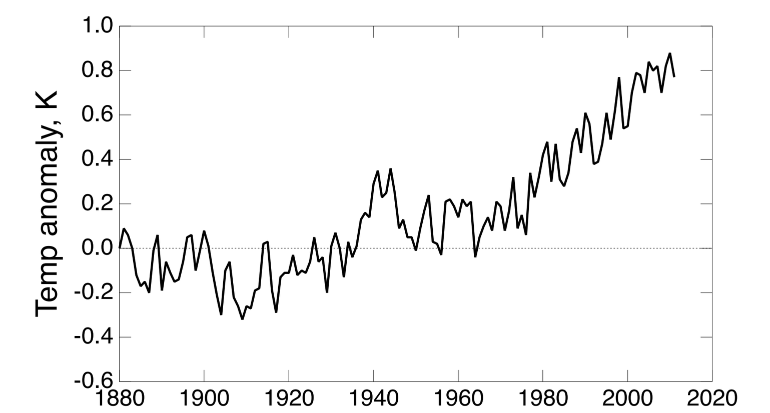
Transient sensitivity, 0.48 K/(W m^{-2})

MODELED FORCING, *MEASURED* TEMP CHANGE

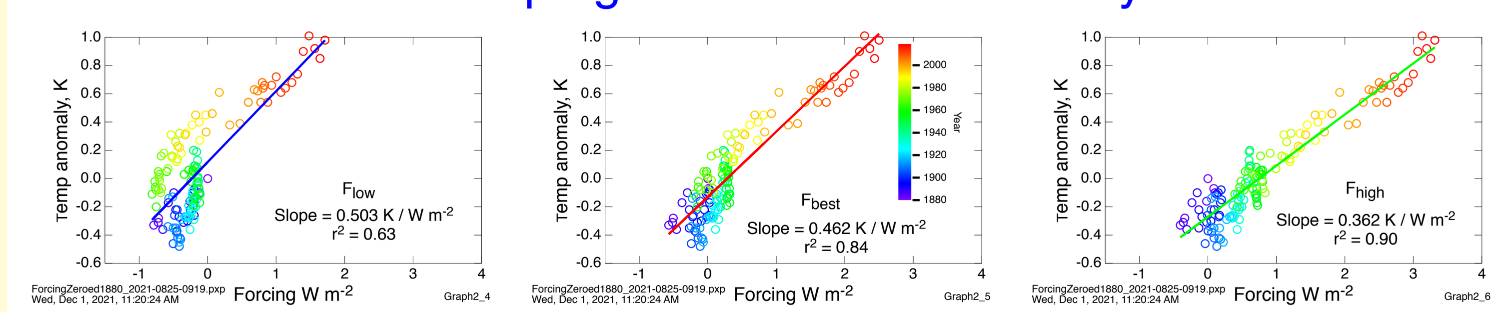
AR6 best estimate and 5-95% bounds on historical forcing. Higher total forcing corresponds to lower aerosol forcing magnitude.



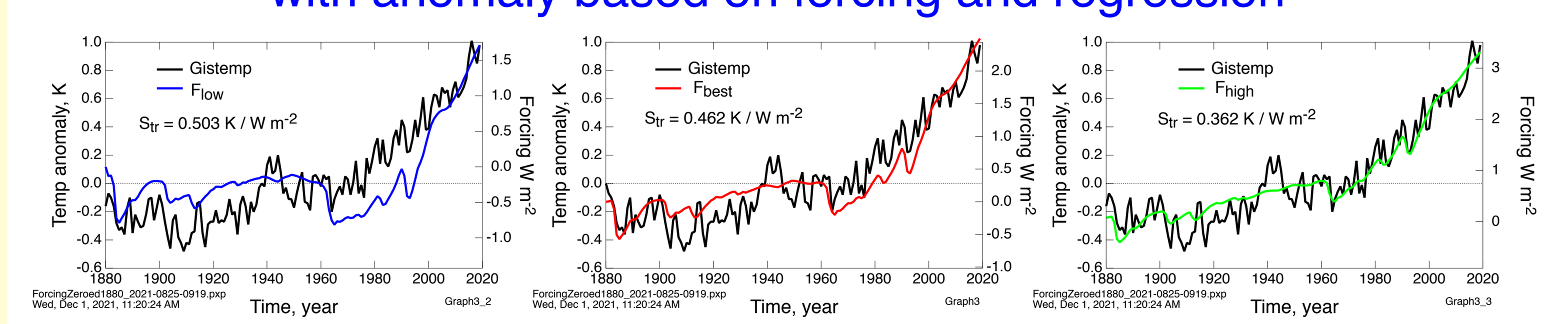
Measured change in global mean surface temperature (GISS)



Regression of temperature anomaly against forcing. Slope gives transient sensitivity.

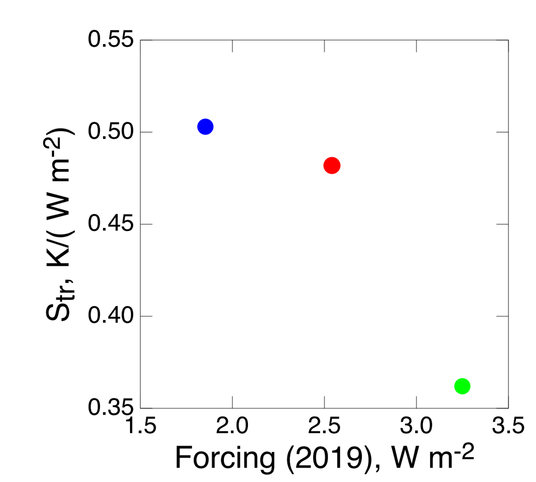


Comparison of measured temperature anomaly with anomaly based on forcing and regression



Transient sensitivity decreases strongly as total forcing increases (aerosol forcing magnitude decreases) – same ΔT but greater total forcing.

Coefficient of variation (r^2) and conformity of forcing and temperature time series ***improve for greater total forcing (lower magnitude aerosol forcing).***



SENSITIVITY DEFINITIONS

Multiple definitions of climate sensitivity are employed in the literature. Definitions used here are given explicitly and related to other definitions.

Transient sensitivity: Ratio of change in global temperature (Global mean surface temperature or Global surface air temperature) that would result from a given forcing, on the time scale of a few decades to a few centuries, to that forcing. S_{tr}. Unit: K/(W m^{-2}).

Equilibrium sensitivity: Ratio of change in global temperature that would ultimately result on attainment of new steady state (so called equilibrium) in response to a given sustained forcing, to that forcing; is attained on time scale of a few millennia. S_{eq}. Unit: K/(W m^{-2}).

Transient climate response (TCR). Increase in global temperature that would result from a 1% per year increase in atmospheric CO_2 at the time (about 69 years) at which atmospheric CO_2 has reached twice its initial amount. Symbol here, ΔT_{TCR}; commonly TCR. Unit : K. Neglecting time lags $\Delta T_{TCR} \approx F_{2X} S_{tr}$, where F_{2X} is the forcing of doubled CO_2, 3.93 W m-2 per IPCC AR6.

Equilibrium climate sensitivity (ECS). Increase in global temperature that would ultimately (a few millennia) result from forcing by sustained doubling of CO_2. Symbol here, ΔT_{ECS}; commonly ECS. $\Delta T_{ECS} = F_{2X} S_{eq}$.

SUMMARY

Total forcing			Low	Best	High
Transient sensitivity	S_{tr}	K/(W m^{-2})	0.50	0.46	0.36
Forcing of doubled CO_2	$F_{2\times}$	W m^{-2}	3.93	3.93	3.93
Transient climate response	TCR, ΔT_{tr}	K	1.98	1.82	1.42
Transient response coeff	$\lambda + \kappa = S_{tr}^{-1}$	W m^{-2} / K	1.99	2.16	2.76
Ocean heat uptake coeff	κ	W m^{-2} / K	0.69	0.69	0.69
Equilibrium response coeff	λ	W m^{-2} / K	1.30	1.48	2.07
Equilibrium sensitivity	S_{tr}	K/(W m^{-2})	0.77	0.68	0.48
Equilibrium climate sensitivity	ECS, ΔT_{eq}	K	3.03	2.66	1.90

CONCLUSIONS

Based on observed time series of temperature change and modeled time series of forcing, Earth's transient climate sensitivity is 0.46 K / (W m^{-2}) with 5-95% uncertainty range 0.50-0.36 K /(W m^{-2}).This corresponds to TCR 1.82 (1.98-1.42) K and ECS 2.66 (3.03-1.90) K.

Total forcing at high end of range (weaker aerosol forcing), corresponding to ***lower climate sensitivity***, ***exhibits best conformity with temperature anomaly time series.***

Transient climate sensitivity is much more pertinent than equilibrium sensitivity to climate change on the multi-decadal to multi-century time scale.

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