INVERSE CALCULATION OF AEROSOL FORCING

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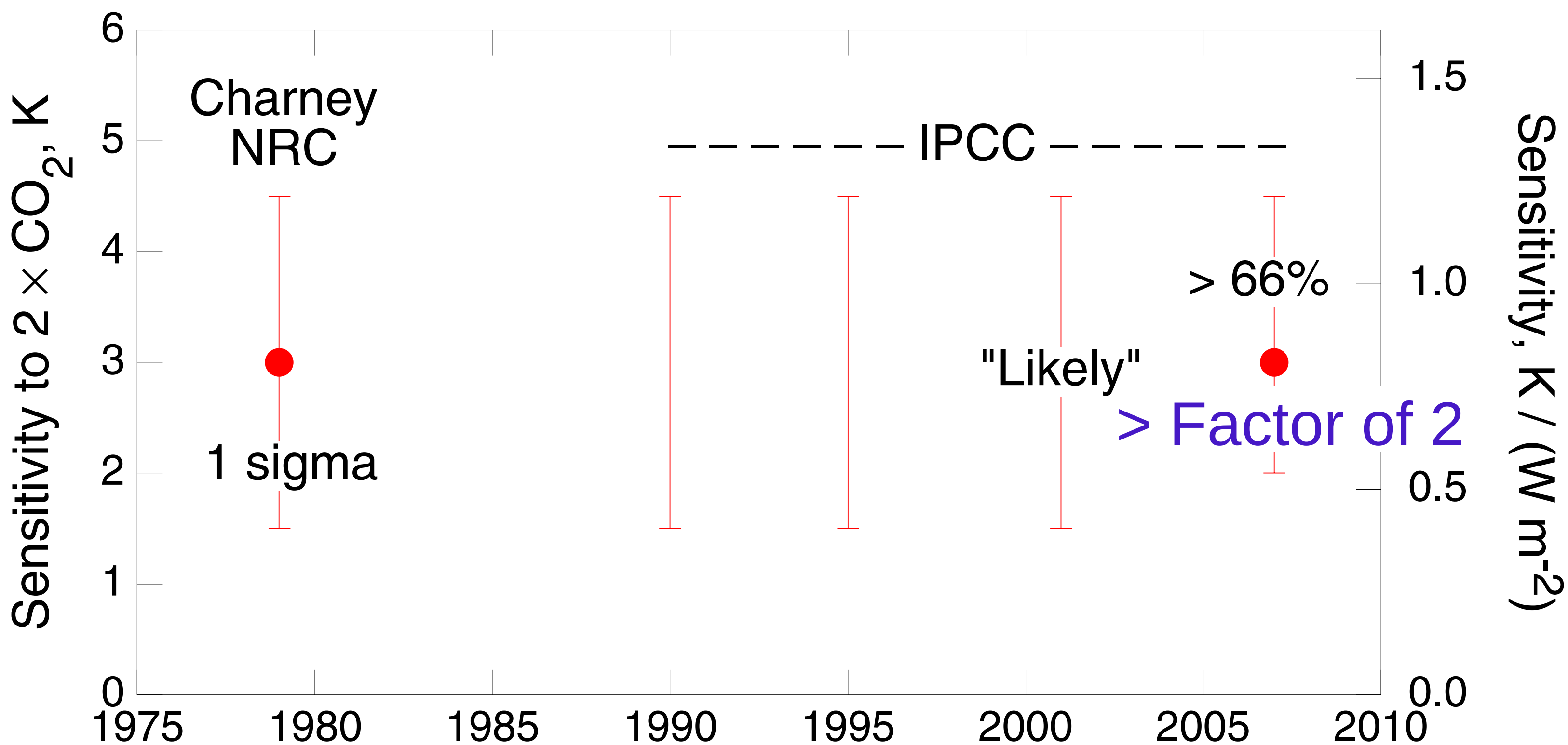
OUTLINE

- Climate forcing, sensitivity, and response
- Forcings and their uncertainties.
- Implications of uncertainties in forcings.
- Inverse calculation of forcings.
- Determination of climate sensitivity from energy balance model of Earth's climate system.
- Determination of total forcing and aerosol forcing over the twentieth century.
- Concluding observations.

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

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



IMPLICATIONS OF UNCERTAINTY IN CLIMATE SENSITIVITY

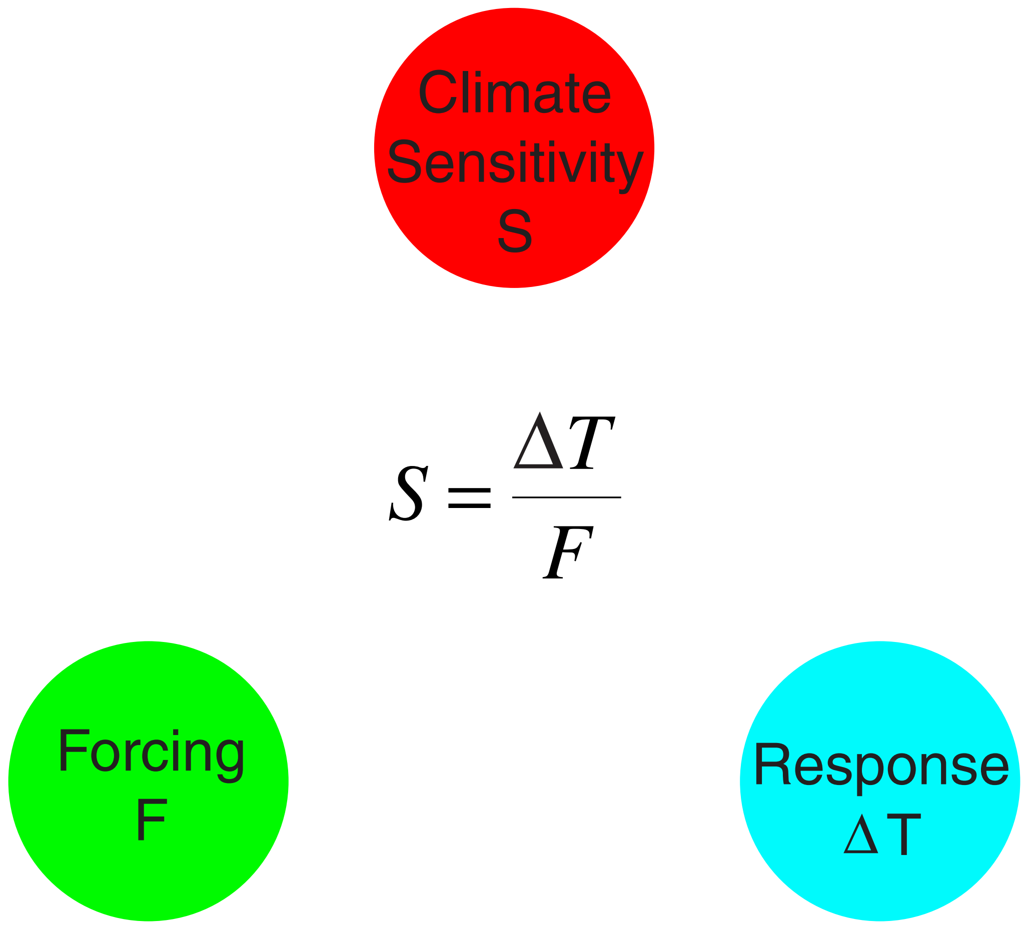
Uncertainty in climate sensitivity translates directly into . . .

- Uncertainty in the amount of ***incremental atmospheric*** **CO_2** that would result in a given increase in global mean surface temperature.
- Uncertainty in the amount of ***fossil fuel carbon*** that can be combusted consonant with a given climate effect.

At present this uncertainty is more than a factor of 2.

THE FORCING – SENSITIVITY – RESPONSE TRIANGLE

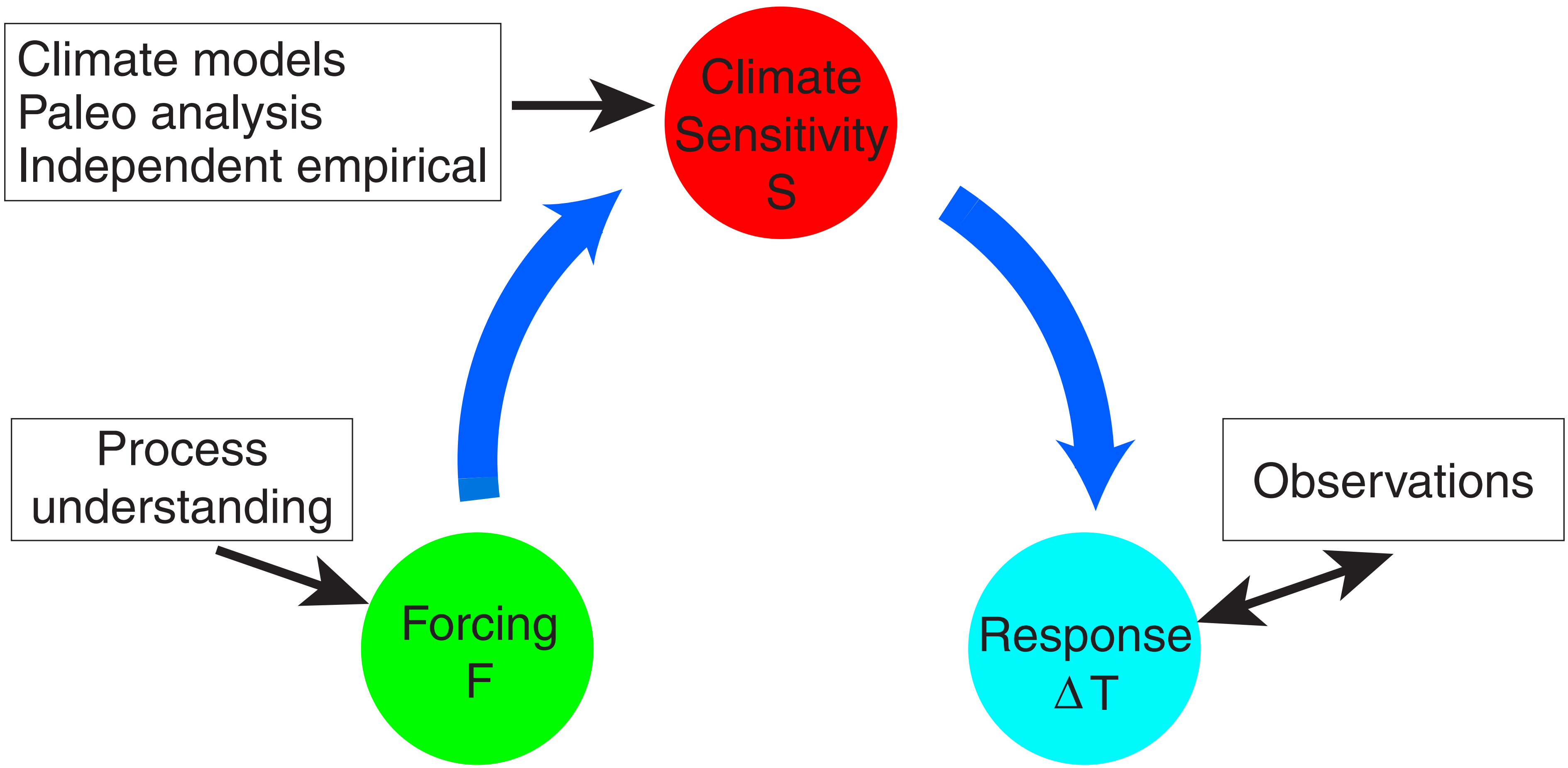
Knowledge of any two quantities yields the third.



$$S = \frac{\Delta T}{F}$$

FORWARD CALCULATION OF CLIMATE FORCING AND RESPONSE

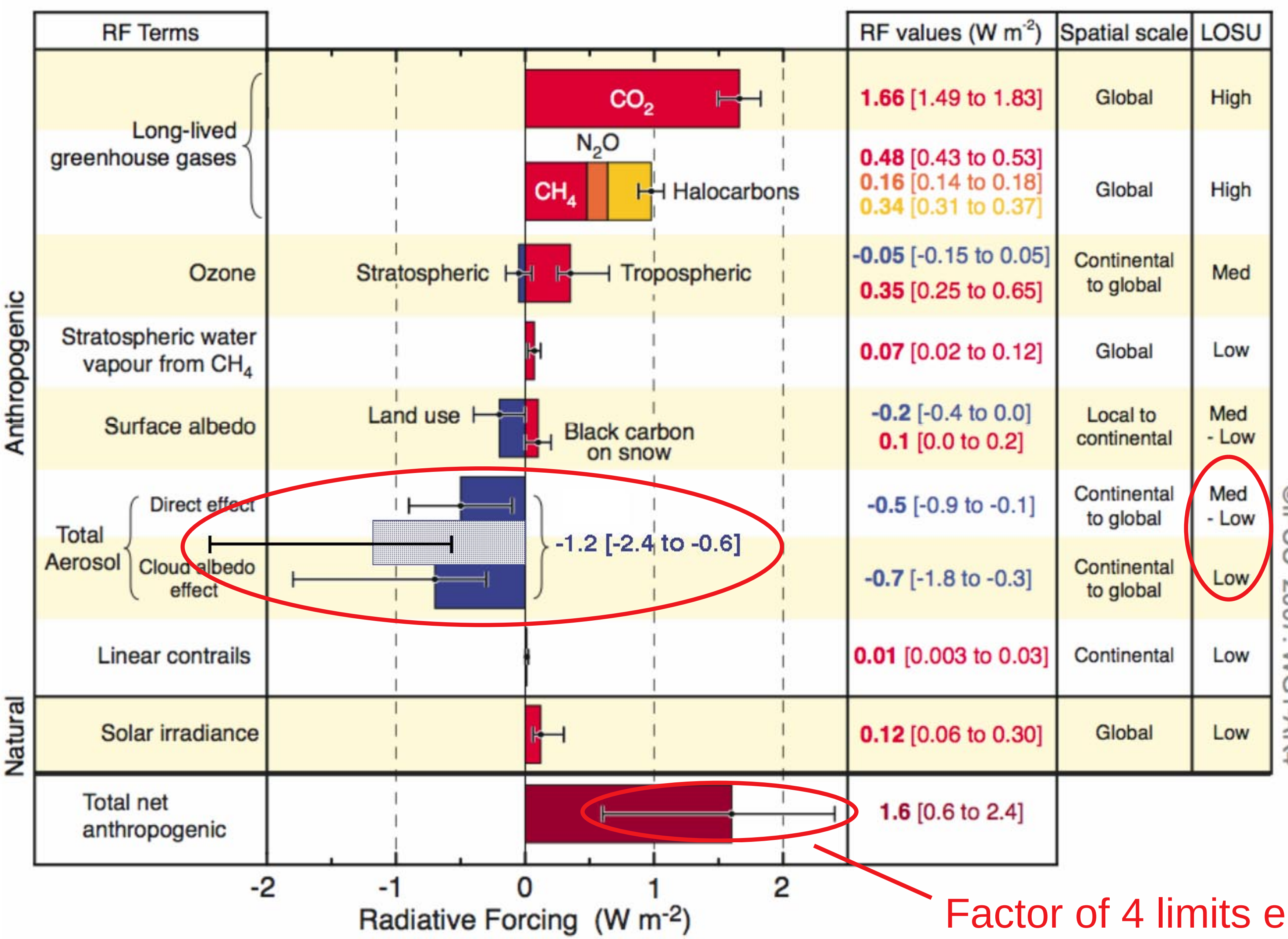
Requires independent knowledge of forcing and climate sensitivity

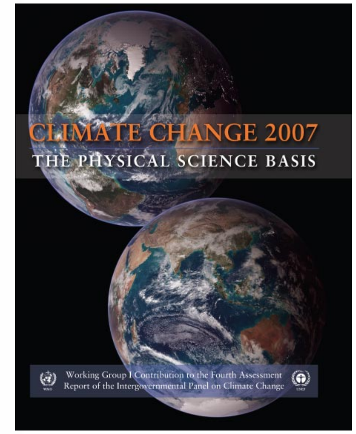


Compare modeled and observed response.
Could get the “right” answer for the wrong reason.

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

Pre-industrial to present (Intergovernmental Panel on Climate Change, 2007)

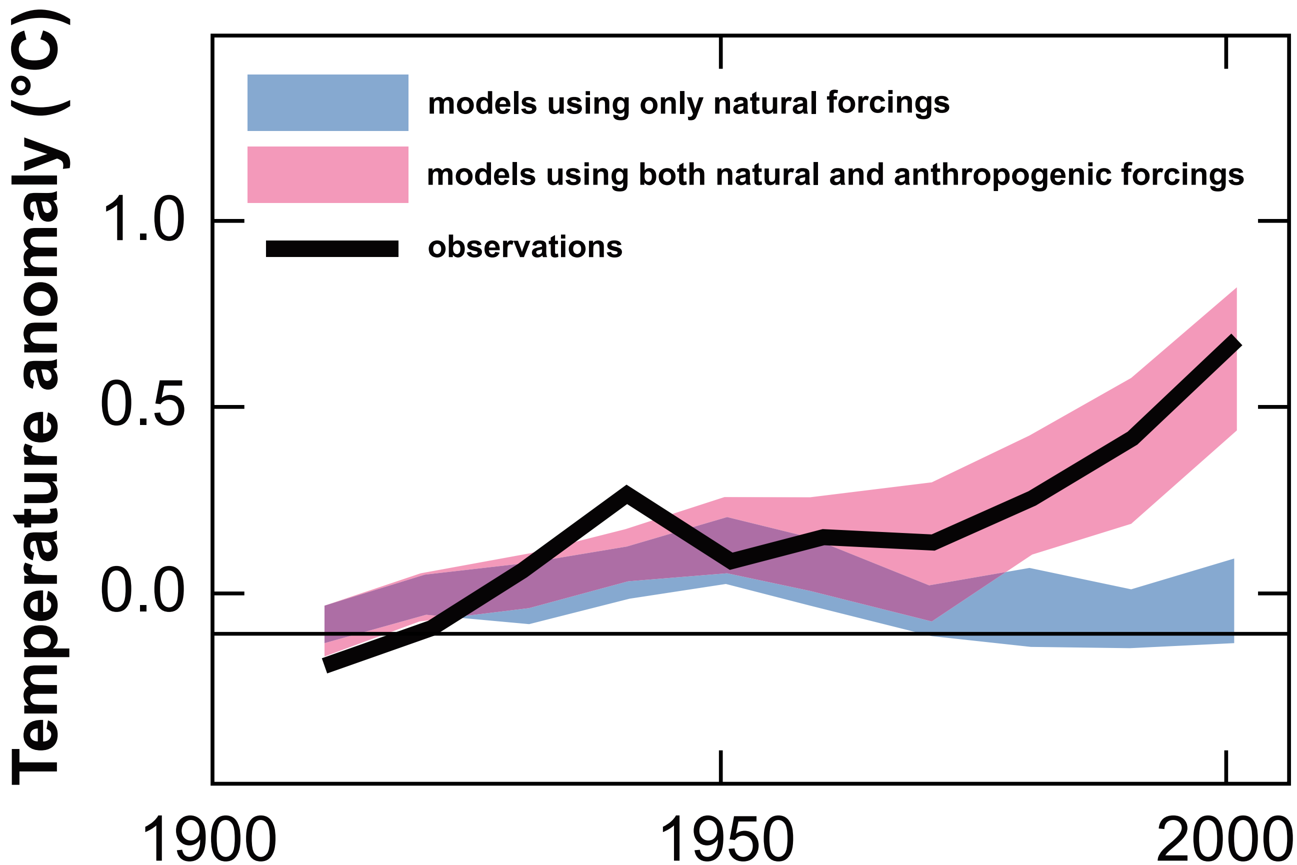




LOSU denotes level of scientific understanding.

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models

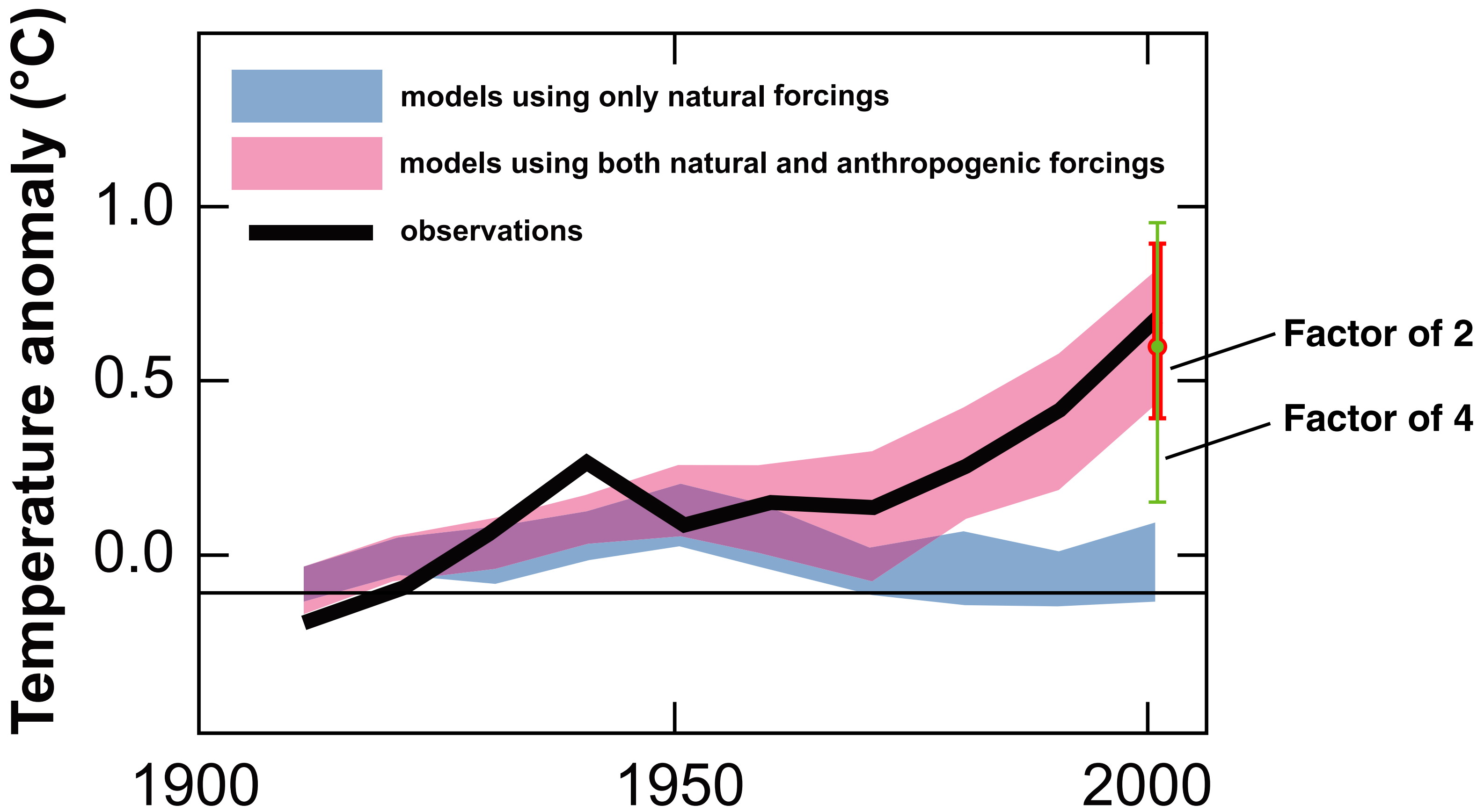


“ Models can … simulate many observed aspects of climate change over the instrumental record. One example is that the ***global temperature trend over the past century … can be modelled with high skill when both human and natural factors that influence climate are included***.

IPCC AR4, 2007

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007

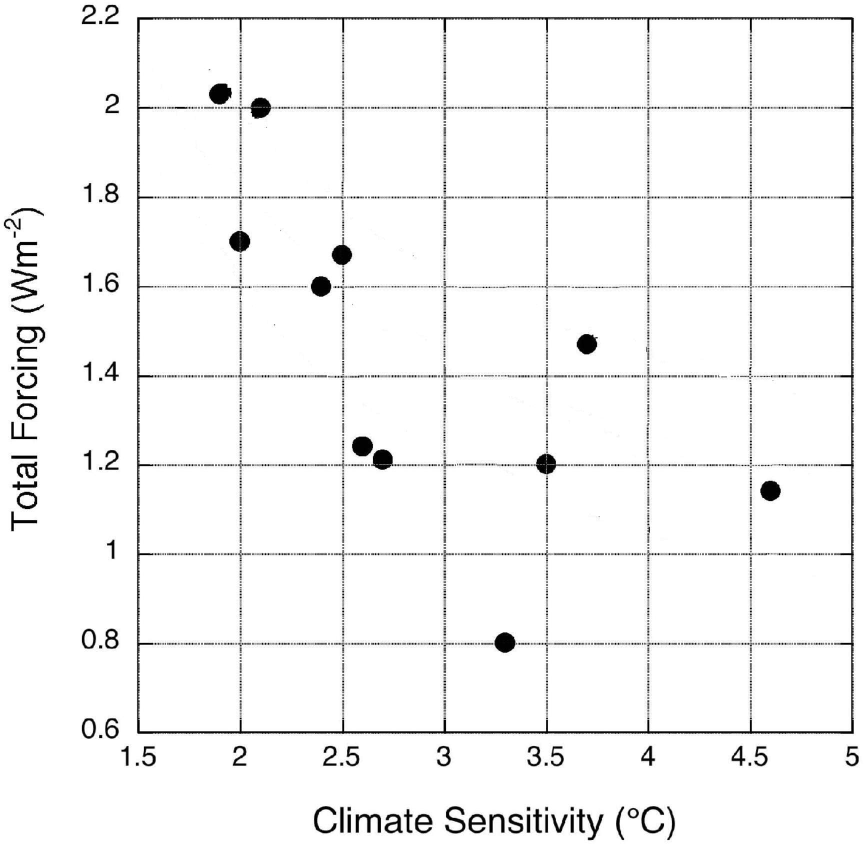
Uncertainty in modeled temperature increase – less than a factor of 2, red – is ***well less than uncertainty in forcing*** – a factor of 4, green.

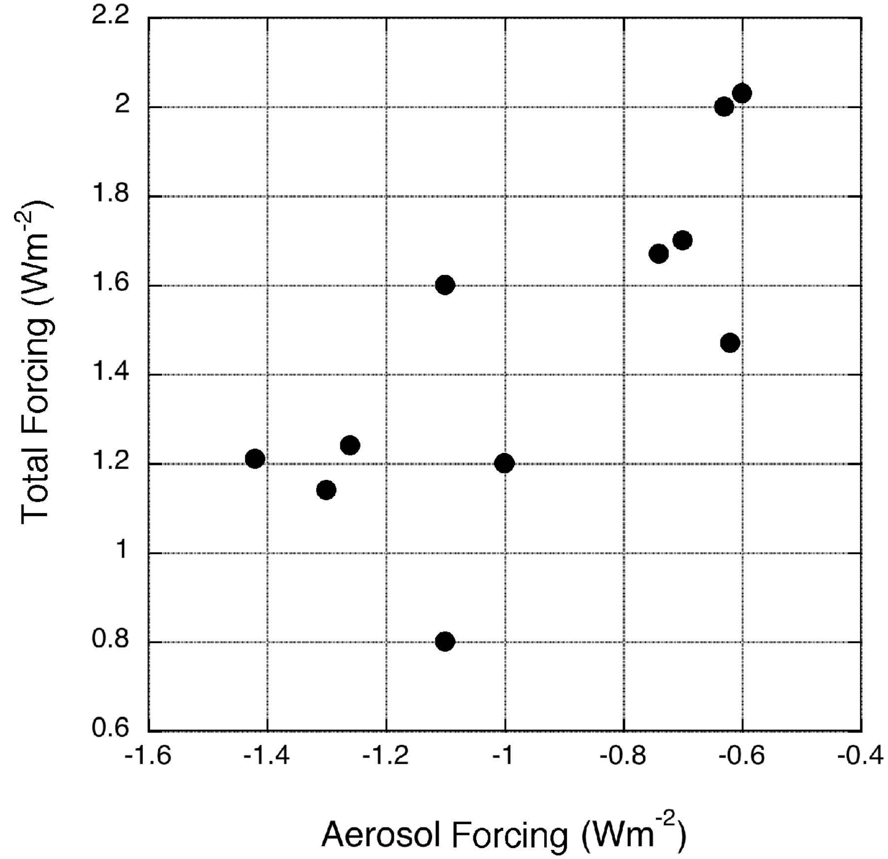
The models ***did not span the full range of the uncertainty*** and/or . . .

The forcings used in the model runs were ***anticorrelated with the sensitivities of the models***.

CORRELATION OF SENSITIVITY, TOTAL FORCING, AND AEROSOL FORCING IN CLIMATE MODELS

Eleven models used in 2007 IPCC analysis





J. Kiehl, GRL, 2007

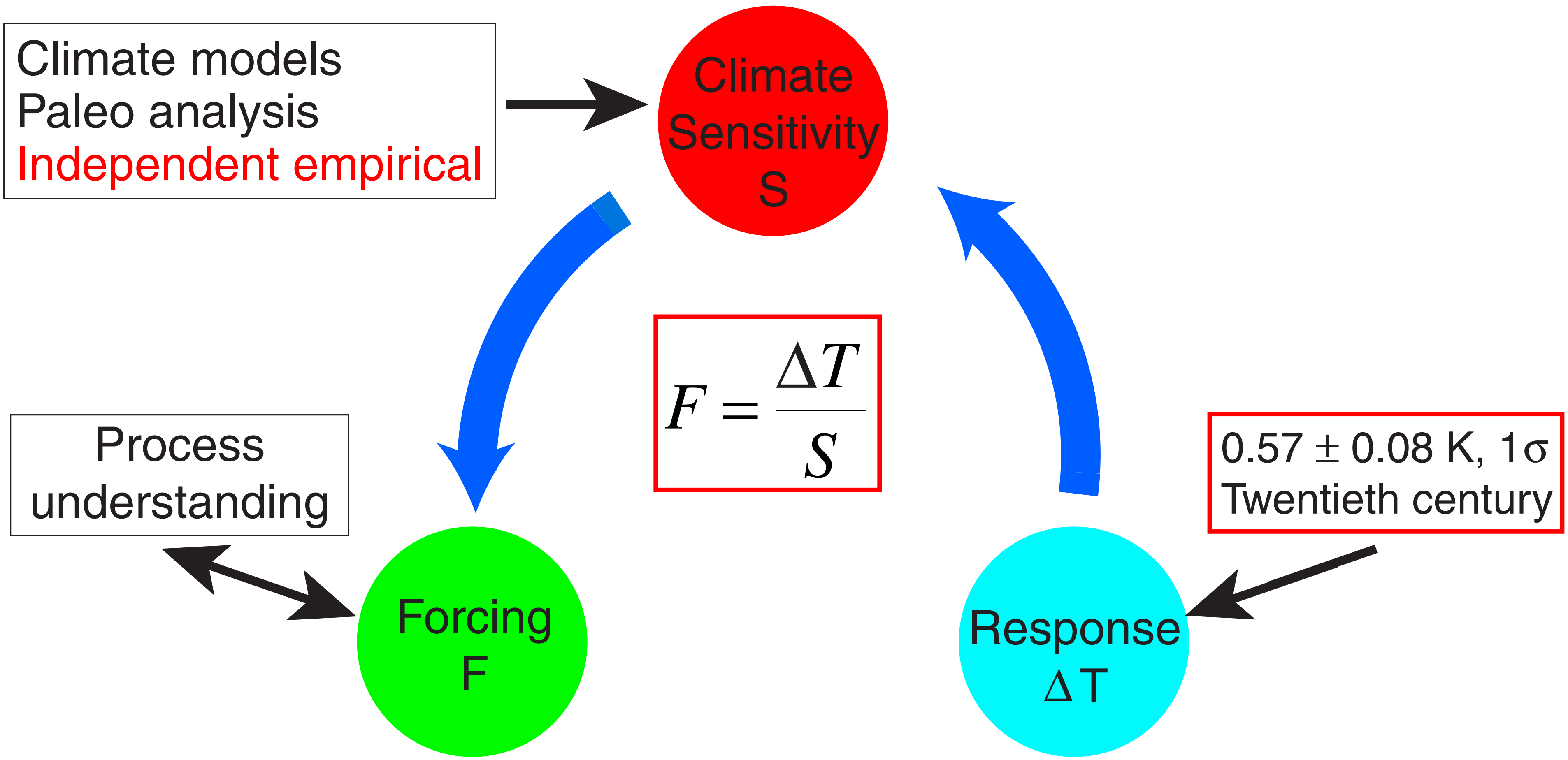
Climate models with higher sensitivity have lower total forcing.

Total forcing increases with decreasing (negative) aerosol forcing.

These models cannot all be correct.

INVERSE CALCULATION OF CLIMATE FORCING

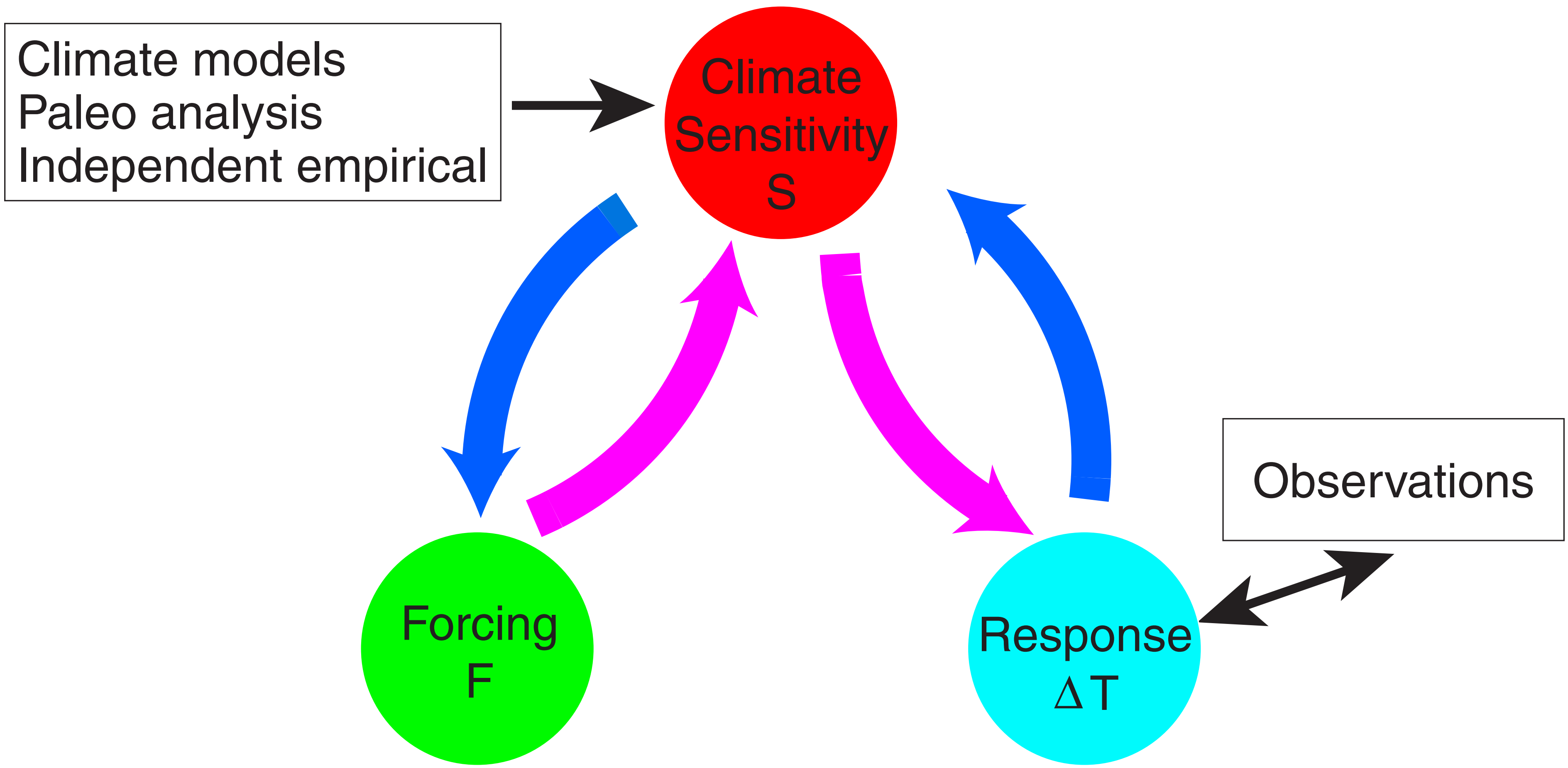
Requires knowledge of climate sensitivity and temperature change



Bound estimates on forcing.

INVERSE CALCULATION OF CLIMATE FORCING

Requires knowledge of climate sensitivity and temperature change



Requires confidence in estimate of climate sensitivity.
Cannot be used to evaluate sensitivity – ***circular reasoning***.

JUST PUBLISHED IN JGR

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Heat capacity, time constant, and sensitivity of Earth's climate system

Stephen E. Schwartz[1]

Received 3 April 2007; revised 14 June 2007; accepted 10 July 2007; published 2 November 2007.

[1] The equilibrium sensitivity of Earth's climate is determined as the quotient of the relaxation time constant of the system and the pertinent global heat capacity. The heat capacity of the global ocean, obtained from regression of ocean heat content versus global mean surface temperature, GMST, is 14 ± 6 W a m^{-2} K^{-1}, equivalent to 110 m of ocean water; other sinks raise the effective planetary heat capacity to 17 ± 7 W a m^{-2} K^{-1} (all uncertainties are 1-sigma estimates). The time constant pertinent to changes in GMST is determined from autocorrelation of that quantity over 1880–2004 to be 5 ± 1 a. The resultant equilibrium climate sensitivity, 0.30 ± 0.14 K/(W m^{-2}), corresponds to an equilibrium temperature increase for doubled CO_2 of 1.1 ± 0.5 K. The short time constant implies that GMST is in near equilibrium with applied forcings and hence that net climate forcing over the twentieth century can be obtained from the observed temperature increase over this period, 0.57 ± 0.08 K, as 1.9 ± 0.9 W m^{-2}. For this forcing considered the sum of radiative forcing by incremental greenhouse gases, 2.2 ± 0.3 W m^{-2}, and other forcings, other forcing agents, mainly incremental tropospheric aerosols, are inferred to have exerted only a slight forcing over the twentieth century of -0.3 ± 1.0 W m^{-2}.

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

Global energy balance: $C\frac{dT_s}{dt} = \frac{dH}{dt} = Q - E = \gamma J - \varepsilon\sigma T_s^4$

C is heat capacity coupled to climate system on relevant time scale

T_s is global mean surface temperature

H is global heat content

Q is absorbed solar energy

E is emitted longwave flux

J is $\frac{1}{4}$ solar constant

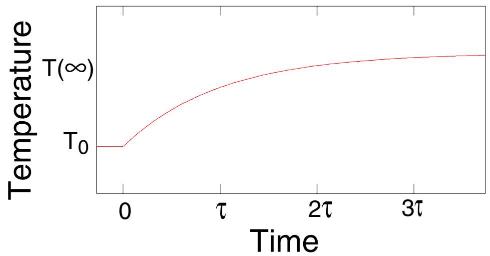
γ is planetary co-albedo

σ is Stefan-Boltzmann constant

ε is effective emissivity

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

Apply step-function forcing: $F = \Delta(Q - E)$



At "equilibrium" $\Delta T_S(\infty) = SF$

Stefan-Boltzmann sensitivity

S is equilibrium climate sensitivity $S = f\dfrac{T_0}{4\gamma_0 J_S}$ K / (W m^{-2})

f is feedback factor

$$f = \frac{1}{\left(1 - \frac{1}{4}\frac{d\ln\gamma}{d\ln T}\Big|_0 + \frac{1}{4}\frac{d\ln\varepsilon}{d\ln T}\Big|_0\right)}$$

Time-dependence: $\Delta T_S(t) = SF(1 - e^{-t/\tau})$

τ is climate system time constant $\tau = CS$ or $S = \tau / C$

One equation in three unknowns

APPROACH TO DETERMINE EARTH'S CLIMATE SENSITIVITY

Empirically determine heat capacity C and time constant τ of Earth's climate system from observations over the instrumental period.

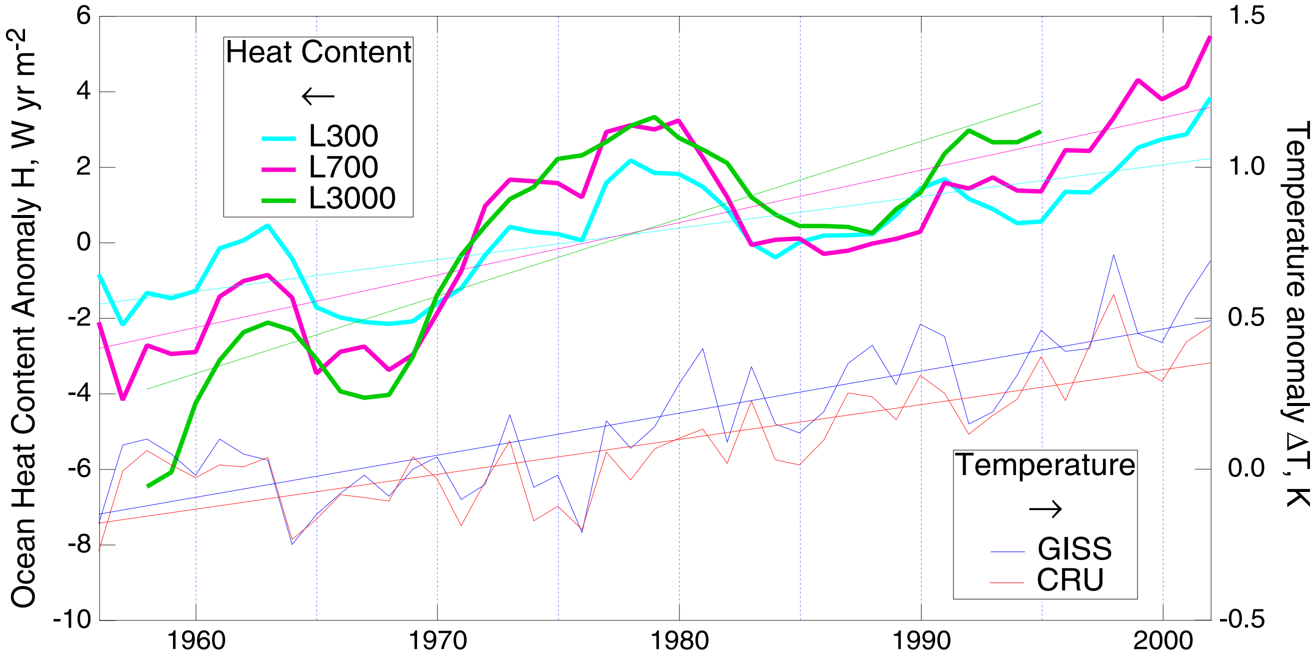
Evaluate sensitivity as $S = \tau/C$.

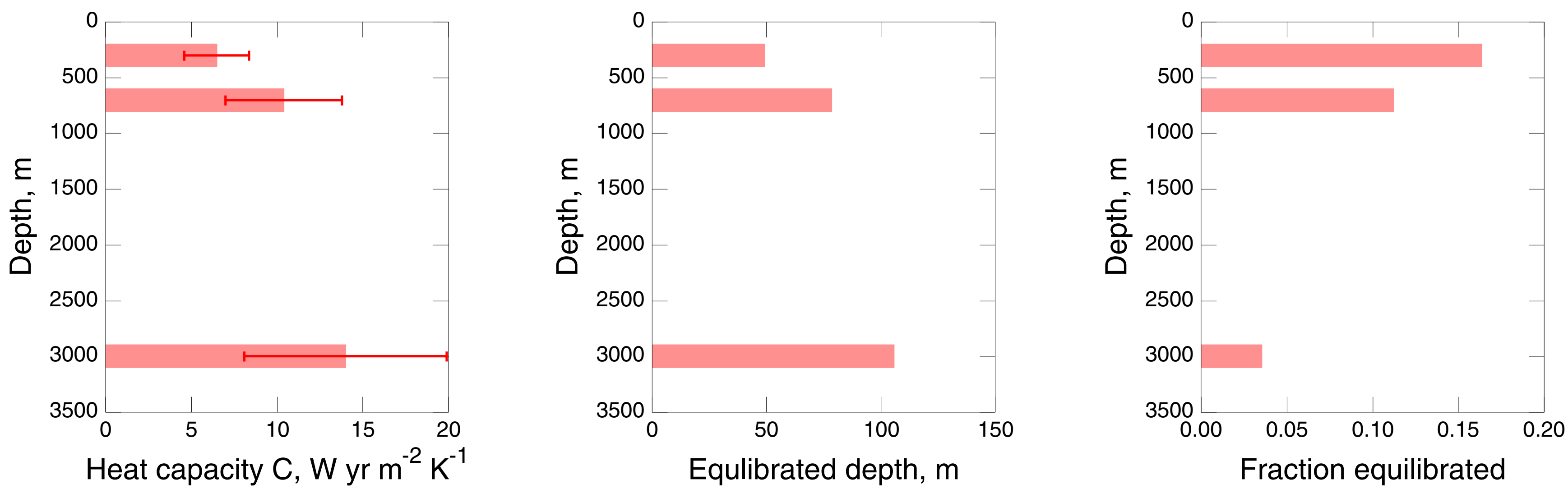
EMPIRICAL DETERMINATION OF OCEAN HEAT CAPACITY

$$C = \frac{dH/dt}{dT_s/dt}$$

Surface temperature
T_s: GISS, CRU

Ocean heat content
H: Levitus *et al.*,
GRL, 2005

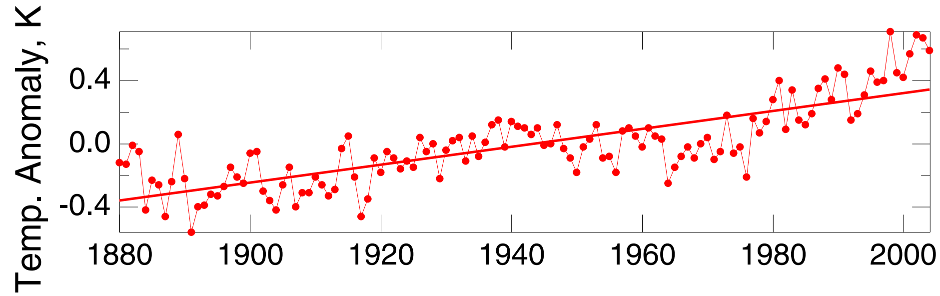




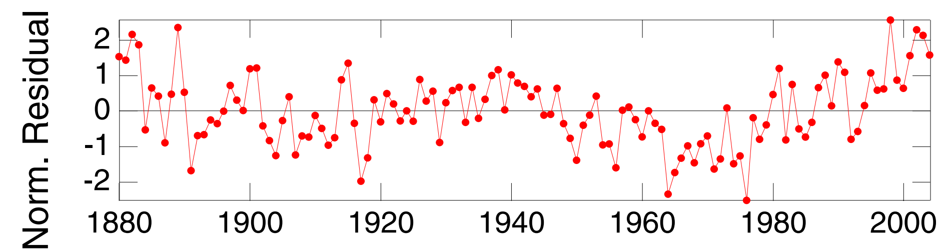
- ~50% of heat capacity is between surface and 300 m.
- Other heat sinks raise global heat capacity to 17 ± 7 W yr m^{-2} K^{-1}.

DETERMINATION OF TIME CONSTANT OF EARTH'S CLIMATE SYSTEM FROM AUTOCORRELATION OF TIME SERIES

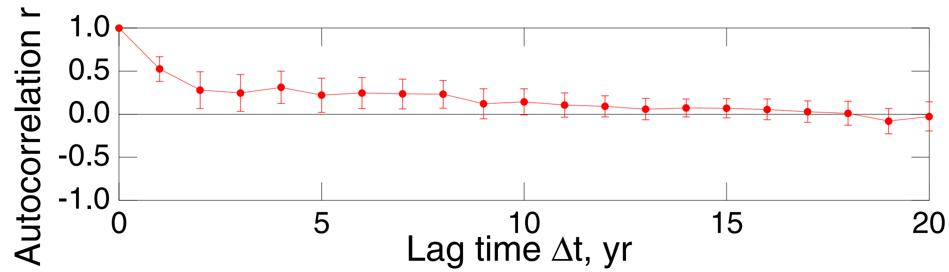
Annual global mean surface temperature anomaly T_s



Remove long term trend; plot the residuals

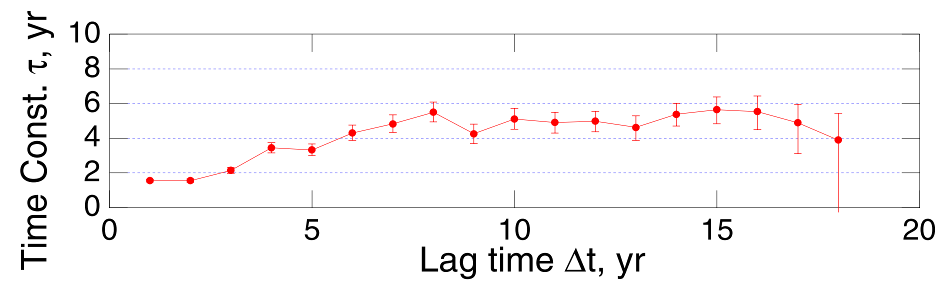


Calculate autocorrelogram (& standard deviations; Bartlett, 1948)



Calculate time constant τ for relaxation of system to perturbation (Leith, 1973)

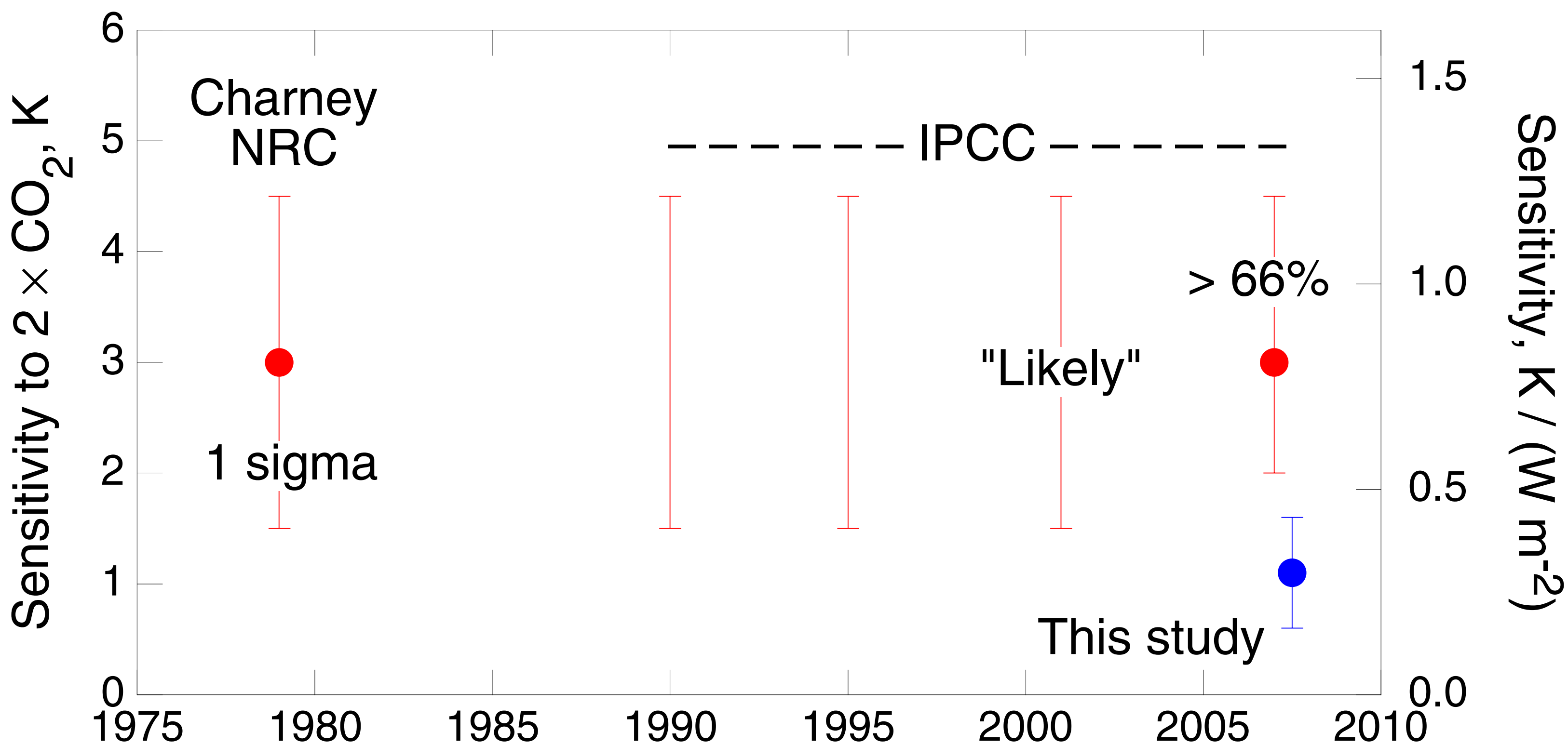
$$\tau(\Delta T) = -\Delta T \,/\ln r(\Delta T)$$



- This is the ***e-folding time constant*** for relaxation of global mean surface temperature to perturbations on the decadal scale.
- On decadal scale time constant ***asymptotes to 5 ± 1 yr***.

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

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



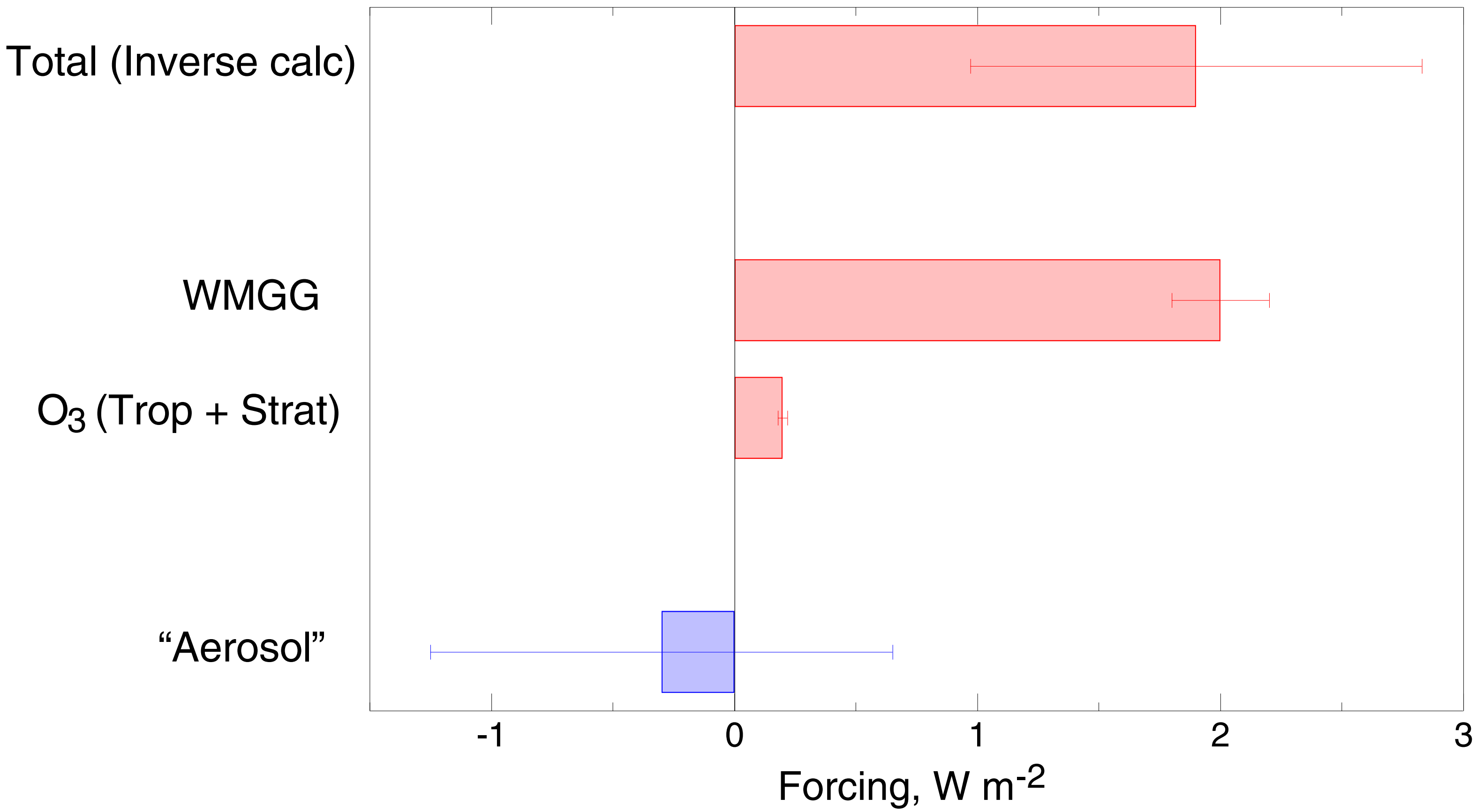
Sensitivity obtained in this study is much lower than that from climate models and paleo studies.

SUMMARY RESULTS

Quantity	Unit	Value	1 σ
Effective global heat capacity C	W yr m^{-2} K^{-1}	**17**	**7**
Effective climate system time constant τ	yr	**5**	**1**
Equilibrium climate sensitivity $S = \tau / C$	K/(W m^{-2})	**0.30**	**0.14**
Equilibrium temperature increase for $2 \times CO_2$, $\Delta T_{2\times}$	K	**1.1**	**0.5**
Total forcing over the 20th century, $F_{20} = \Delta T_{20} / S$	W m^{-2}	**1.9**	**0.9**
Forcing in 20th century other than GHGs (*mainly aerosols*), $F_{20}^{other} = F_{20} - F_{20}^{ghg}$	W m^{-2}	**-0.3**	**1.0**
Lag in temperature change, ΔT_{lag}	K	**0.03**	

INVERSE CALCULATION OF "AEROSOL" FORCING OVER TWENTIETH CENTURY

"Aerosol" forcing = Total forcing – GHG forcing



Total forcing is dominated by greenhouse gas forcing.

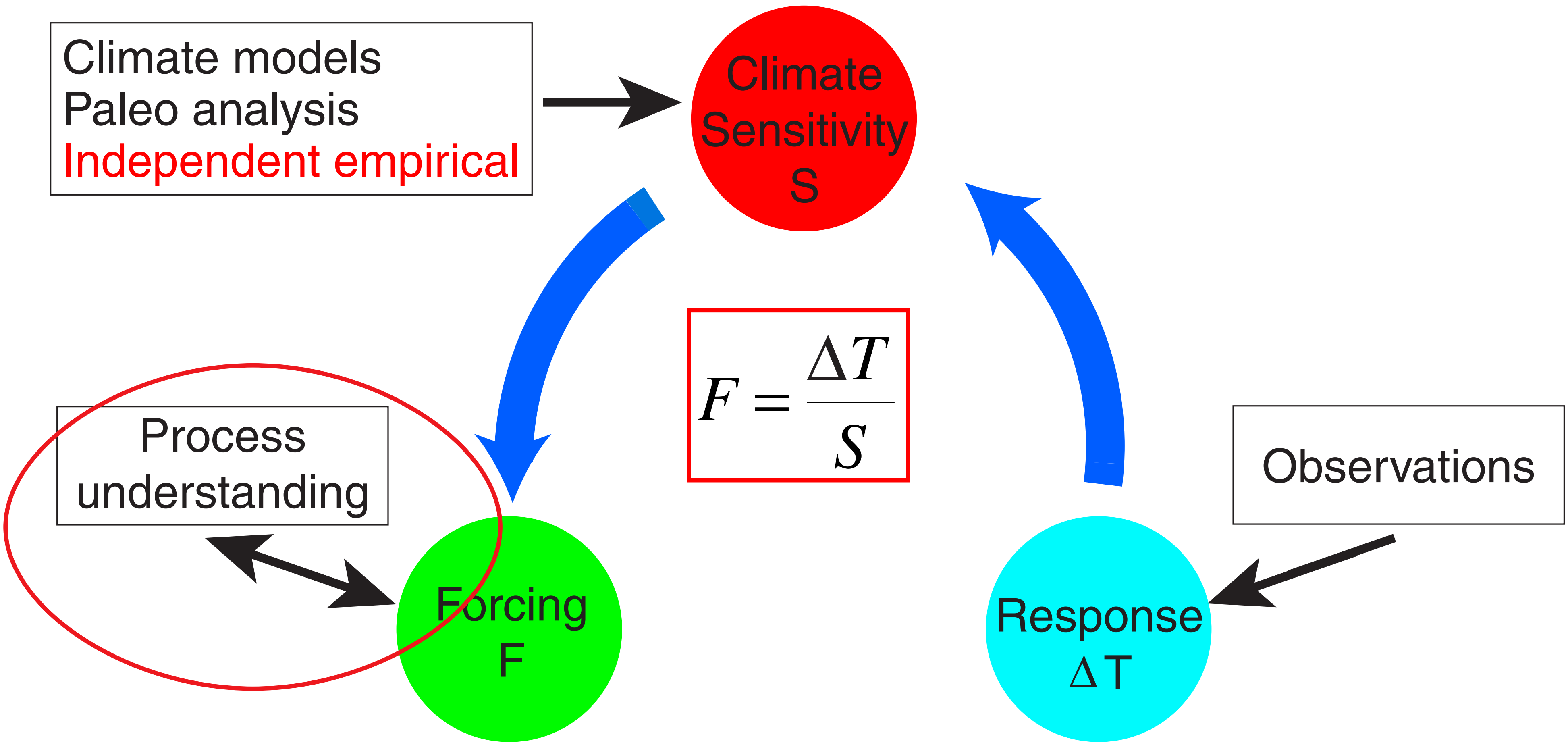
"Aerosol" forcing, calculated as residual, is small, with large uncertainty.

"Aerosol" forcing is presumably dominated by aerosols.

Accuracy of "aerosol" forcing depends on accuracy of total forcing.

INVERSE CALCULATION OF CLIMATE FORCING

Requires knowledge of climate sensitivity and temperature change



Compare to estimates of forcing.

WHAT MIGHT BE WRONG WITH THIS ANALYSIS?

- ***Ocean heat capacity too great***, resulting in low sensitivity.

  Erroneous or nonrepresentative data.

  Obtaining heat capacity from measurements.

- ***Time constant too short***, resulting in low sensitivity.

  Time series too short to give true time constant.

  Detrending emphasizes the rapid fluctuations.

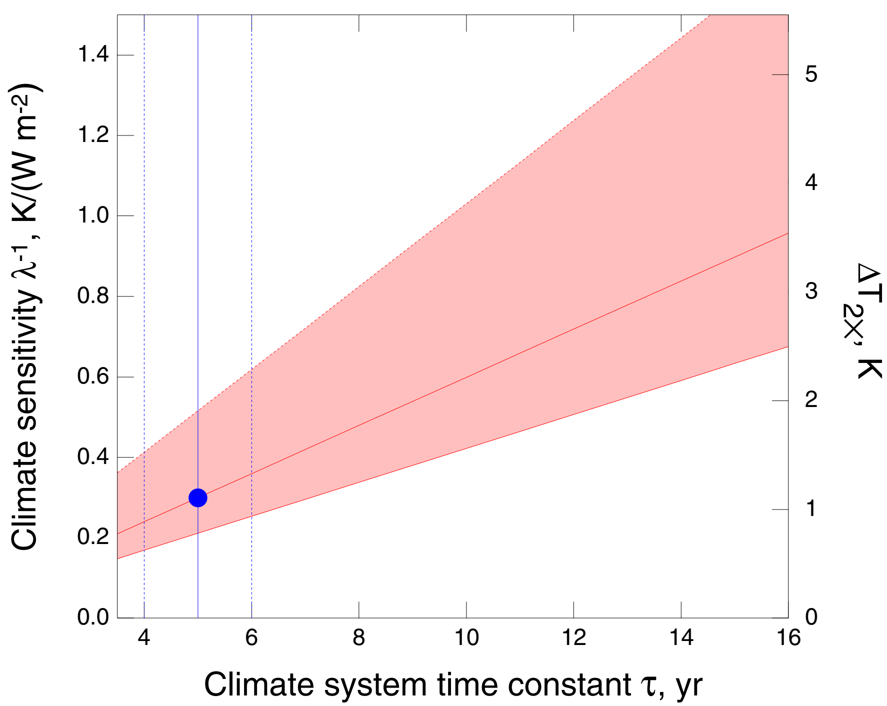
- ***Earth's climate system is much more complex*** than can be represented by a single-compartment model.

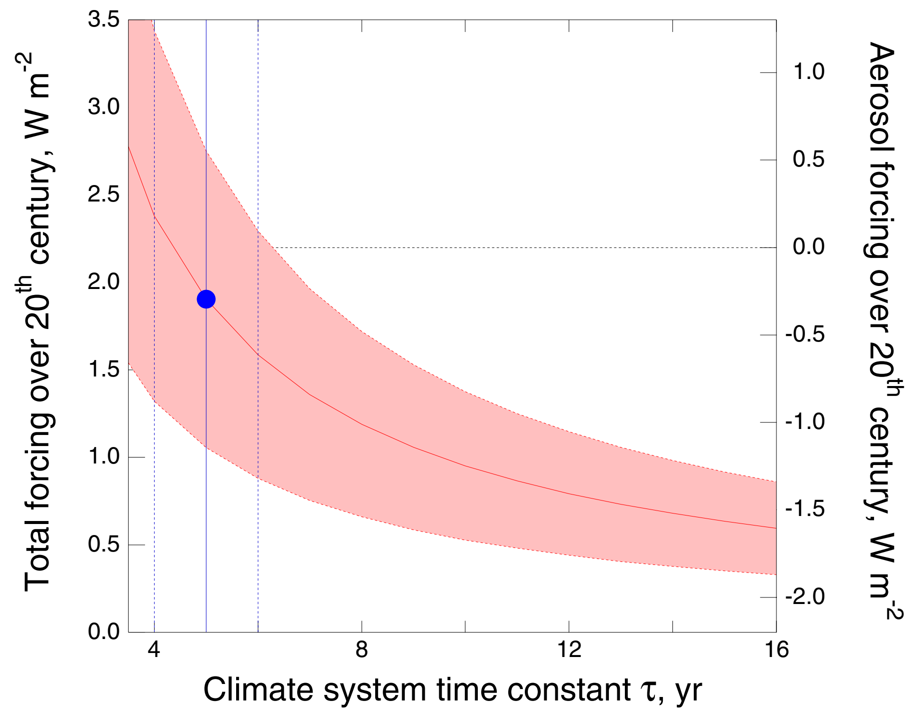
  Multiple time constants, multiple heat capacities.

CLIMATE SENSITIVITY AND INFERRED 20^{th} CENTURY TOTAL AND AEROSOL FORCING

Inverse calculation of forcing as function of climate system time constant τ

$$S = \tau / C \qquad F_{20} = \Delta T_{20} / S = C\Delta T_{20} / \tau \qquad F_{\text{aer}} = F_{20} - F_{\text{GHG}}$$





Time constant from autocorrelation is $\tau = 5 \pm 1$ yr.

Submitted comment suggests τ too small because of length of data record.

Climate sensitivity and inferred forcing depend strongly on time constant.

CONCLUDING OBSERVATIONS

- ***Climate sensitivity*** by energy balance model is **0.30 ± 0.14 K/(W m^{-2})**, (**$\Delta T_{2\times}$ = 1.1 ± 0.5 K**), much lower than current estimates.

- ***Total forcing over the twentieth century*** from inverse calculation is **1.9 ± 0.9 W m^{-2}**.

- ***"Aerosol" forcing over the twentieth century***, calculated as residual, is small negative, **-0.3 ± 0.9 W m^{-2}**.

- This aerosol forcing is ***much less than most present forward calculations***.

? Would I bet the ranch on this analysis?

Viewgraphs available from *www.ecd.bnl.gov/steve/pubs.html*