CONSIDER A SPHERICAL EARTH

HEAT CAPACITY, TIME CONSTANT AND SENSITIVITY OF EARTH'S CLIMATE SYSTEM

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Greenbelt, Maryland

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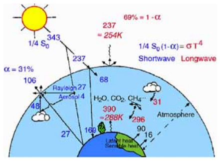
http://www.ecd.bnl.gov/steve

Consider a Spherical Cow

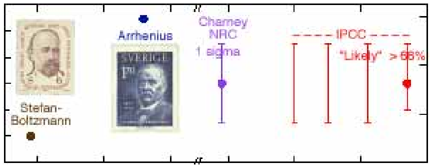
A Course in Environmental Problem Solving

JOHN HARTE

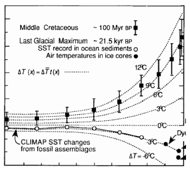
OVERVIEW



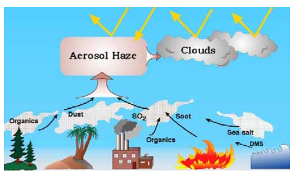
Earth's energy balance and perturbations



Climate sensitivity – definition, importance, past and current estimates



Climate sensitivity from paleoclimate



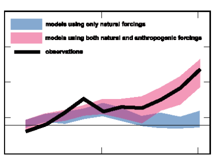
Uncertainty in aerosol forcing and its implications

$$S = \frac{\Delta T}{\Delta F - (dH/dt)}$$

Evaluated for 1957-1994 vs. 1861-1900 for $\Delta F_{2\times} = 3.71$ W m^{-2}

Symbol	Quantity	Value ± 1σ	Unit
ΔT	Temperature change	0.335 ± 0.017	K
ΔF	Forcing	0.35 ± 0.33	W m^{-2}
dH/dt	Planetary heat uptake rate	0.16 ± 0.08	W m^{-2}
S	Climate sensitivity	$0.56^{+>2.2}_{-0.07}$	K/(W m^{-2})
$\Delta T_{2\times}$	ΔT for doubled CO_2	$2.1^{+>8}_{-0.24}$	K

Empirical sensitivity from temperature change over the instrumental record



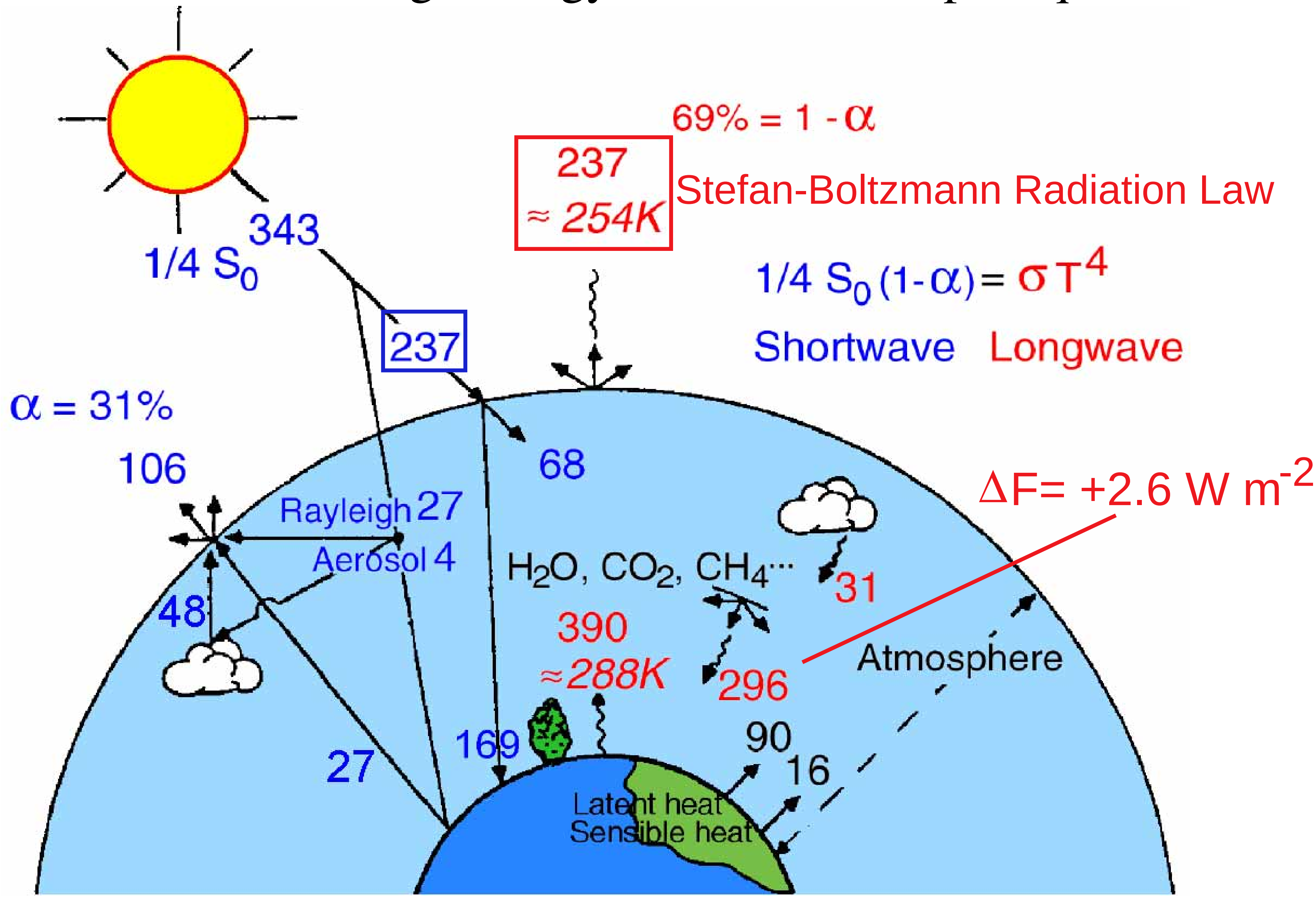
Sensitivity from climate models

Climate sensitivity from whole-earth energy-balance models

Concluding remarks

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



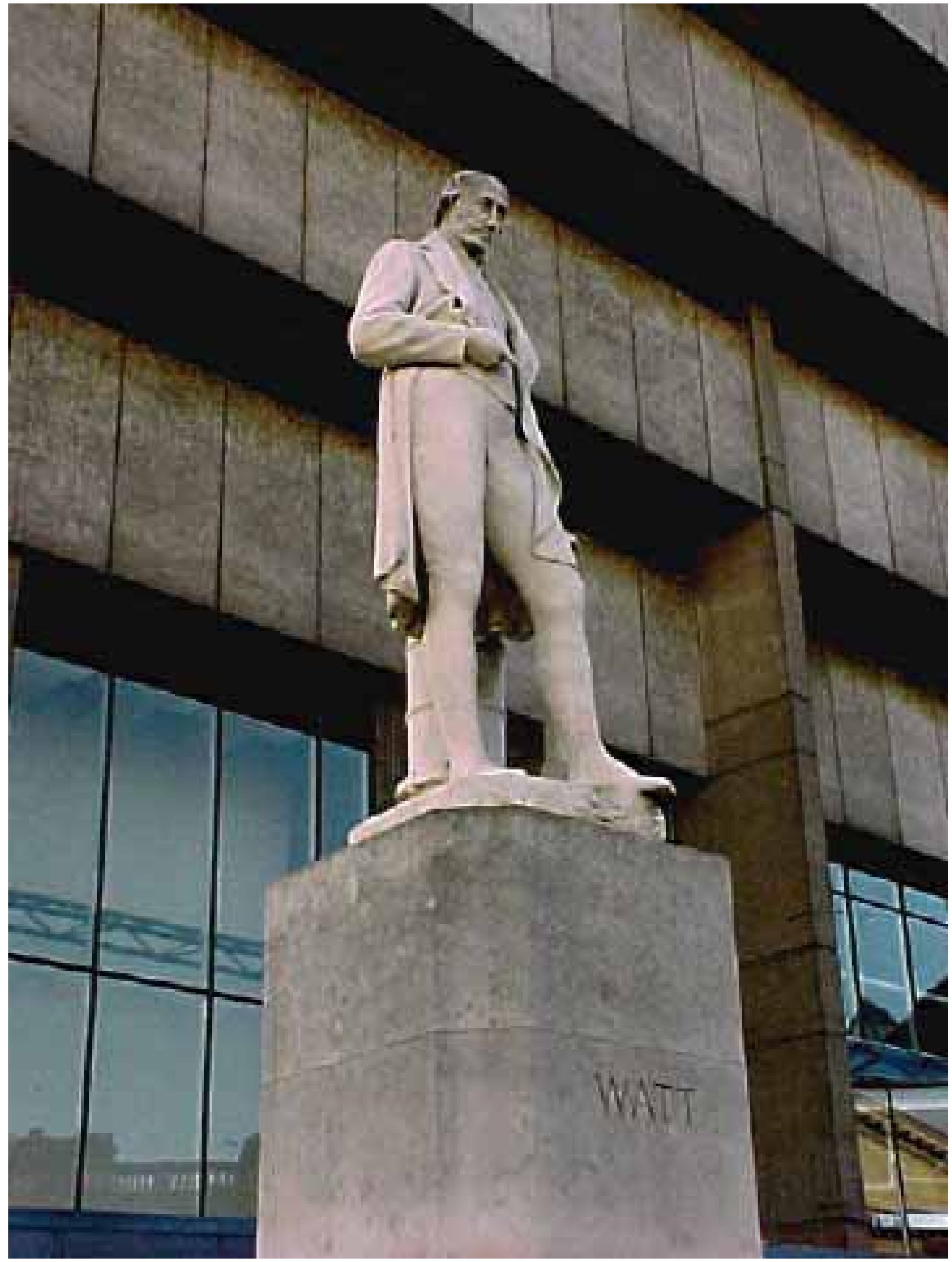
Schwartz, 1996, modified from Ramanathan, 1987

ATMOSPHERIC RADIATION

Power per area

Energy per time per area

Unit:
Watt per square meter
W m^{-2}



RADIATIVE FORCING

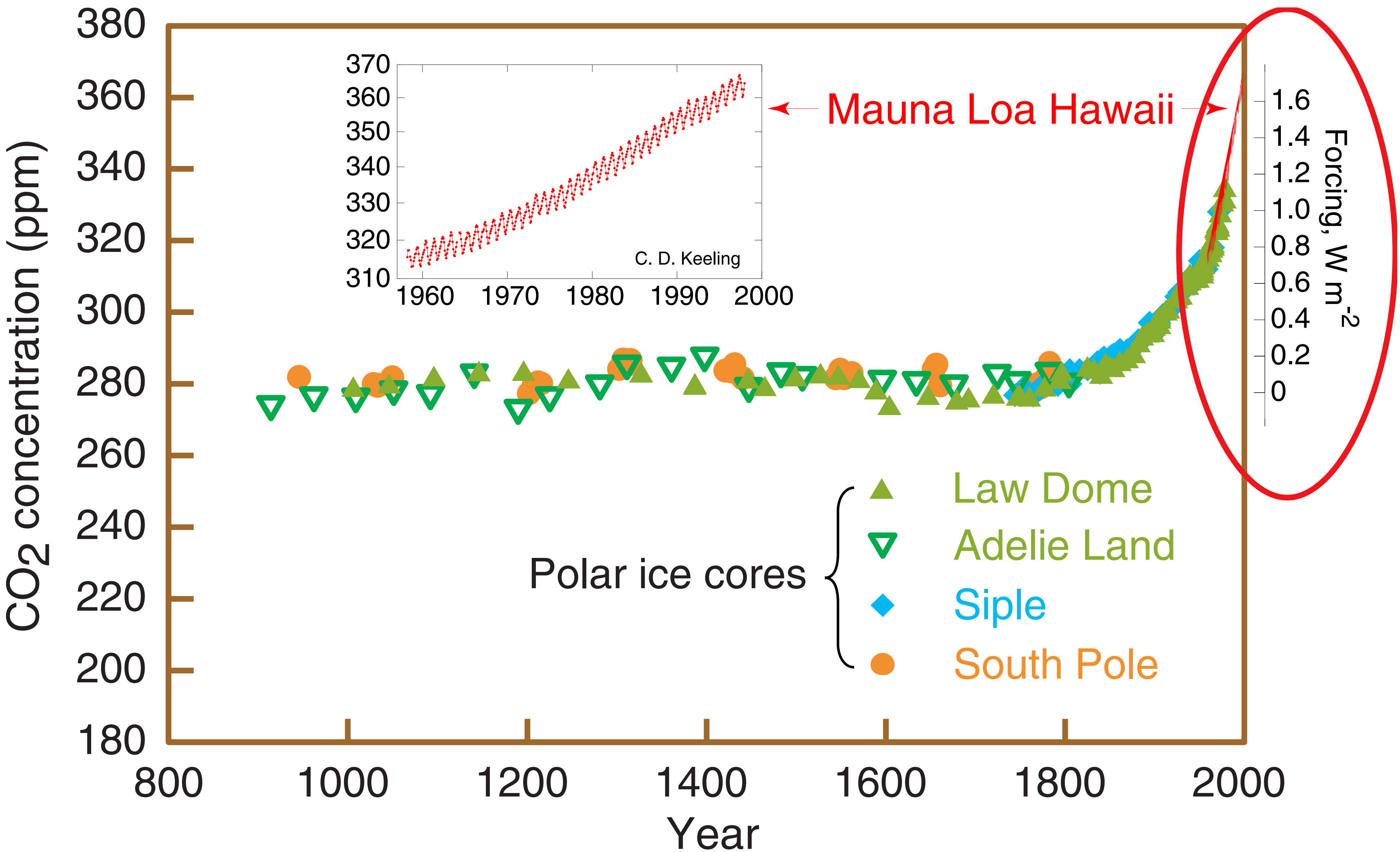
A ***change*** in a radiative flux term in Earth's radiation budget, ΔF, W m^{-2}.

Working hypothesis:

On a global basis radiative forcings are additive and fungible.

- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.

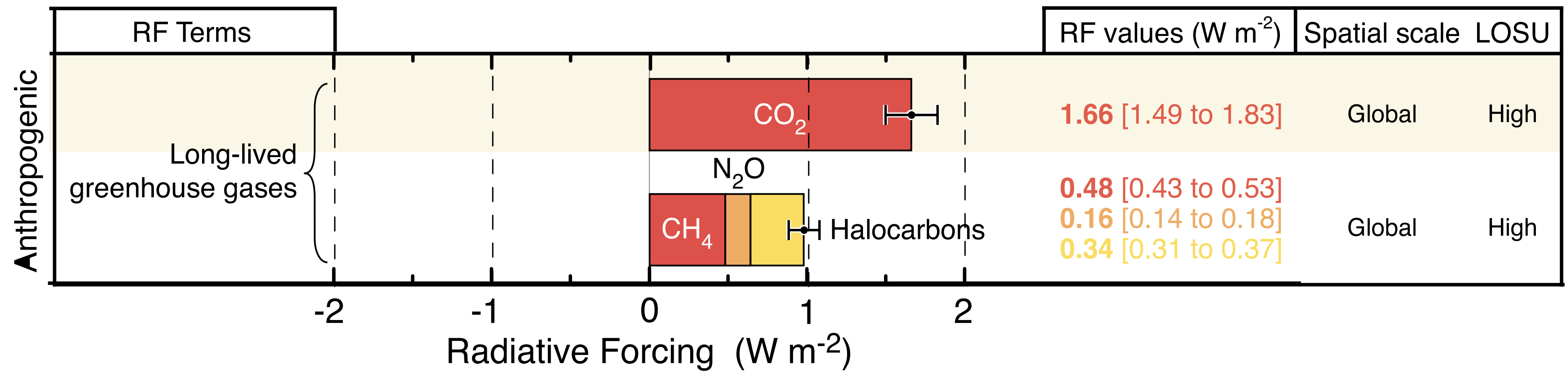
ATMOSPHERIC CARBON DIOXIDE IS INCREASING



Global carbon dioxide concentration and infrared radiative forcing over the last thousand years

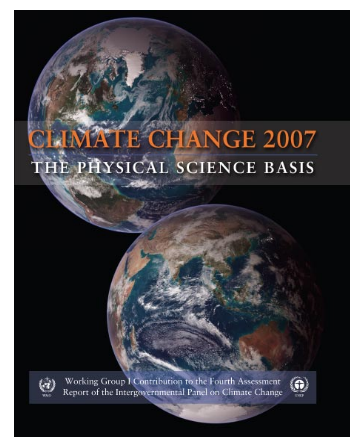
GLOBAL-MEAN RADIATIVE FORCINGS (RF) BY LONG-LIVED GREENHOUSE GASES

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



LOSU denotes level of scientific understanding.

Total radiative forcing: 2.64 ± 0.26 W m^{-2}



CLIMATE RESPONSE

The ***change*** in global and annual mean temperature, ΔT, K, resulting from a given radiative forcing.

Working hypothesis:

The change in global mean temperature is proportional to the forcing, but independent of its nature and spatial distribution.

$$\Delta T = S\,\Delta F$$

CLIMATE SENSITIVITY

The ***change*** in global and annual mean temperature per unit forcing, S, K/(W m^{-2}),

$$S = \Delta T/\Delta F.$$

Climate sensitivity is not known and is the objective of much current research on climate change.

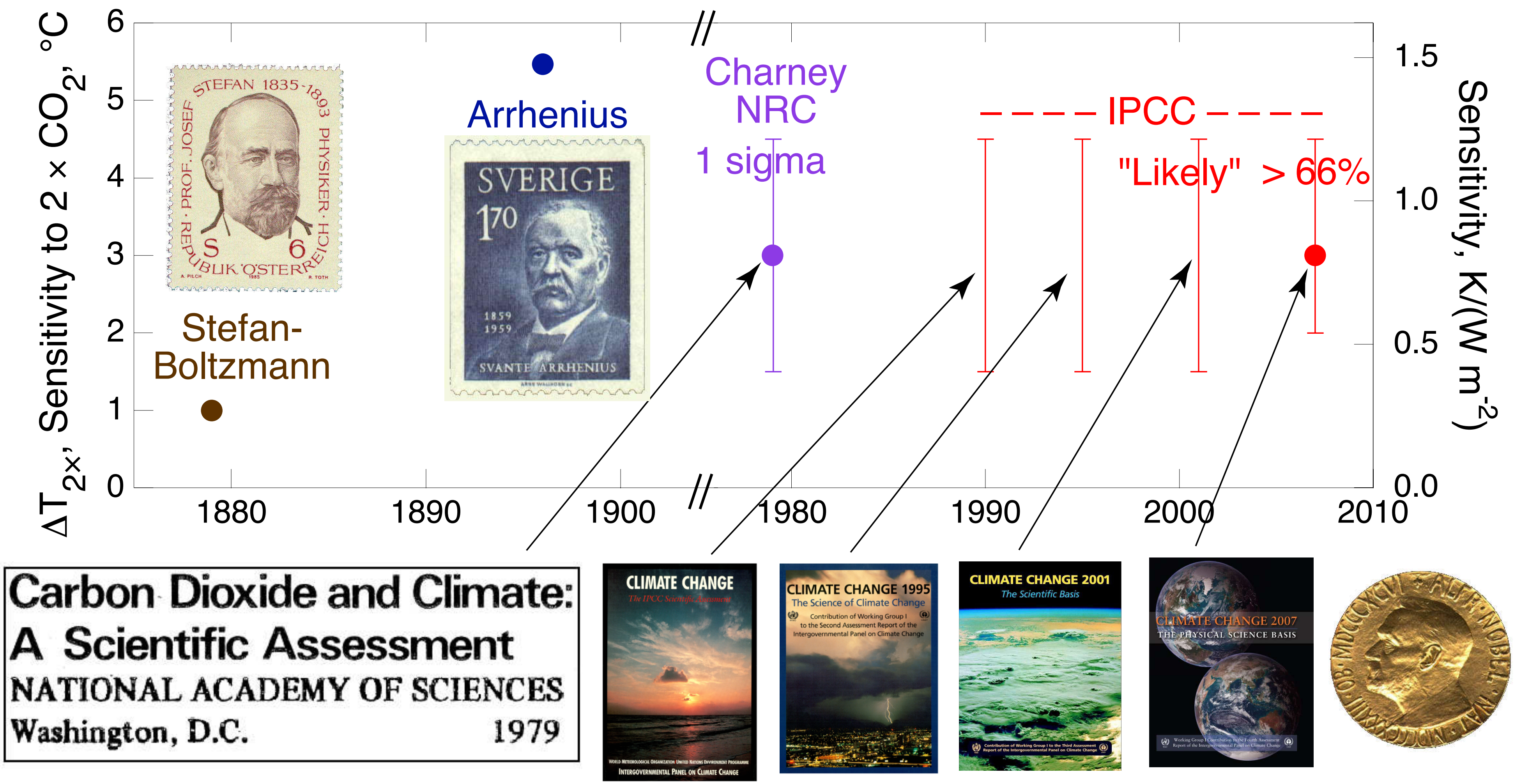
Climate sensitivity is often expressed as the temperature for doubled CO_2 concentration $\Delta T_{2\times}$.

$$\Delta T_{2\times} = S\Delta F_{2\times}$$

$$\Delta F_{2\times} \approx 3.7 \text{ W m}^{-2}$$

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

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



Despite extensive research, climate sensitivity remains ***highly uncertain***.

IMPLICATIONS OF UNCERTAINTY IN CLIMATE SENSITIVITY

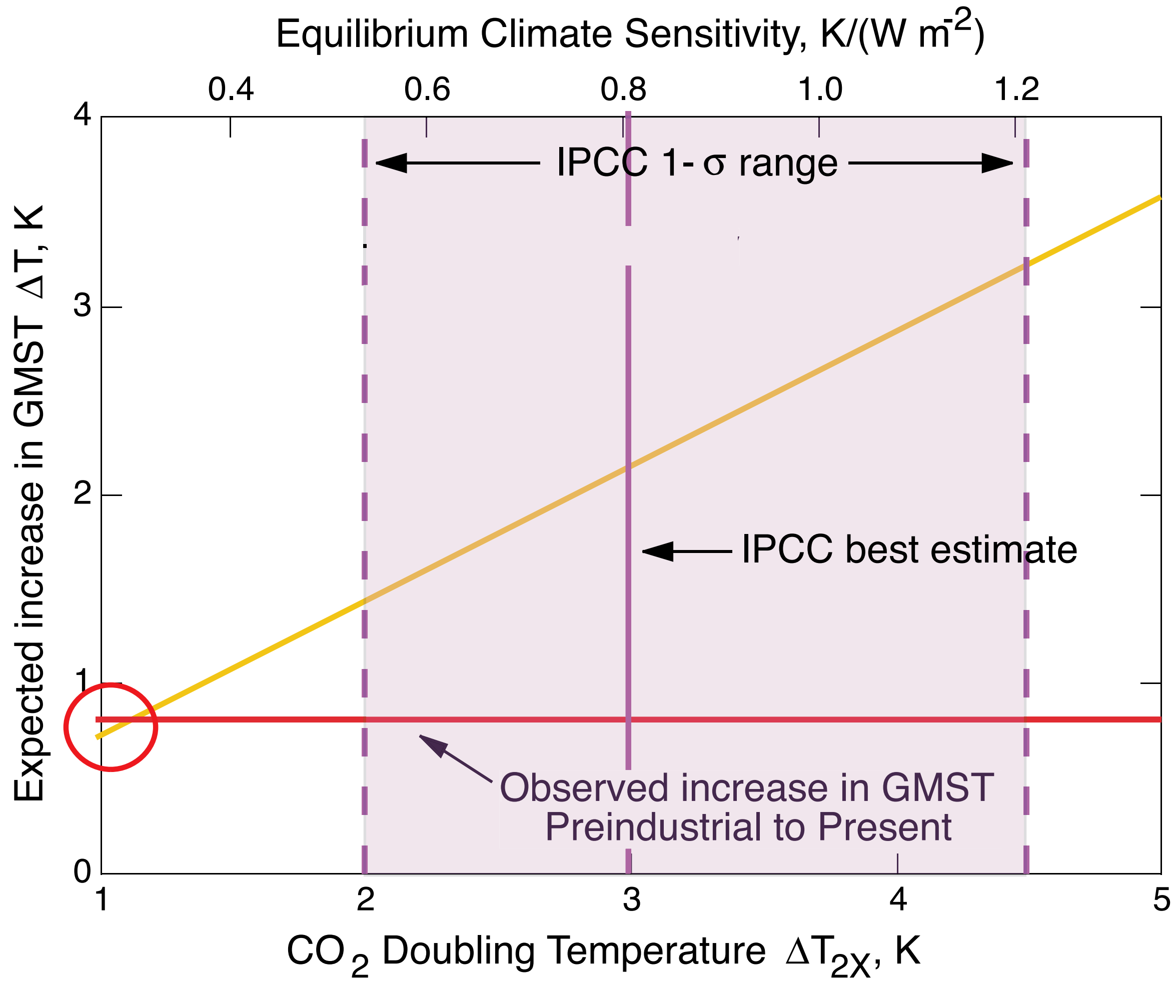
Uncertainty in climate sensitivity results in . . .

- 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.

This uncertainty has major implications on planning the nation's and the world's energy future.

IMPLICATION OF PRESENT GREENHOUSE FORCING

Expected equilibrium increase in global mean surface temperature as function of climate sensitivity for present GHG forcing = 2.64 W m^{-2}

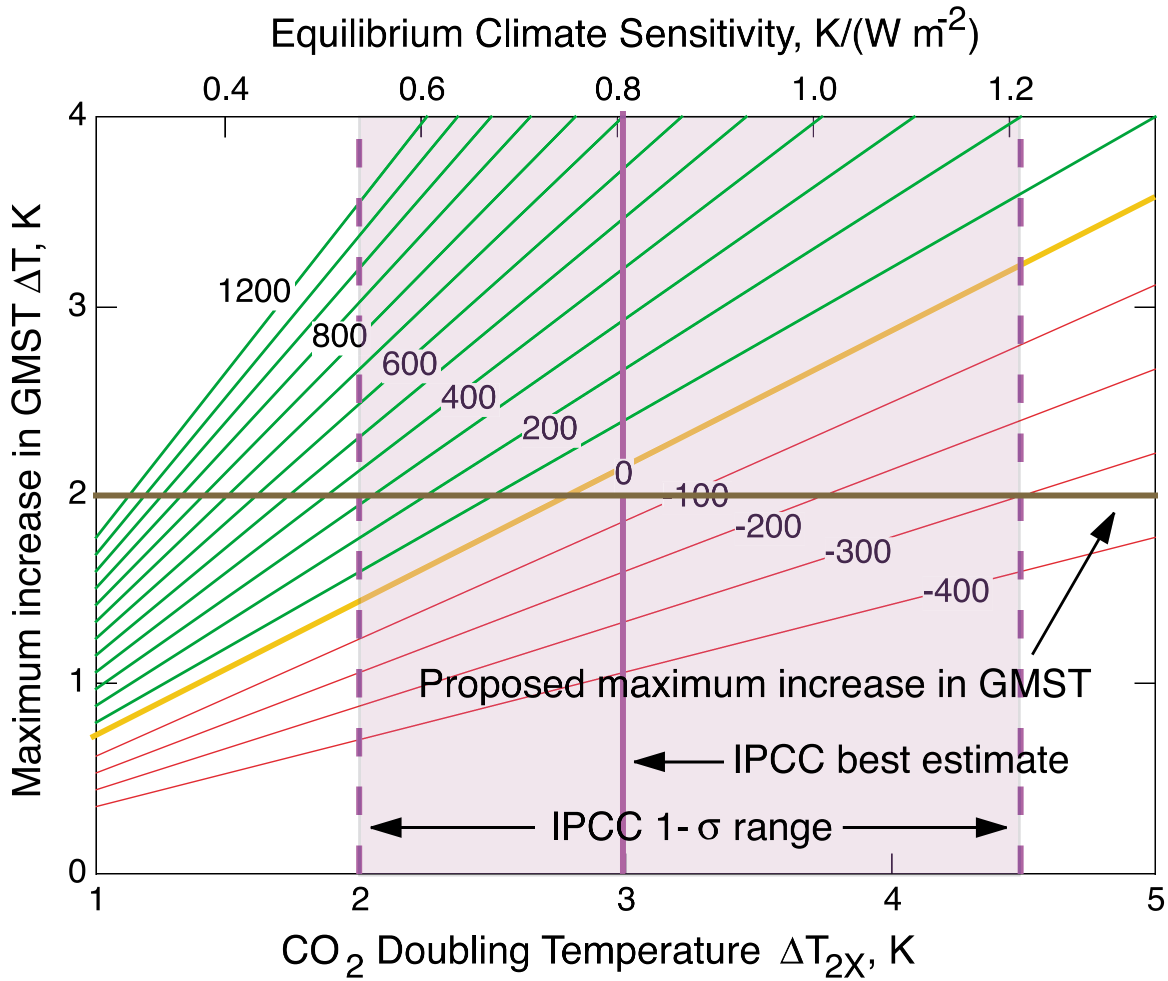


Observed increase in global temperature from preindustrial is 0.8 K.

IPCC 2007 estimate of climate sensitivity, 3 K (range 2.0 – 4.5 K, 1-σ) implies much greater increase in global temperature.

LIMITS ON FUTURE CO_2 EMISSION

Maximum allowable future CO_2 emission (Pg C) for a given allowable increase in global mean surface temperature, as function of climate sensitivity



Commonly accepted maximum increase in global temperature is 2 K.

IPCC 2007 estimate of climate sensitivity is 3 K; range 2.0 – 4.5 K, 1-σ.

Current fossil CO_2 emission rate is ~9 PgC yr^{-1}.

WHY IS OBSERVED INCREASE IN GLOBAL TEMPERATURE SO MUCH LESS THAN EXPECTED?

Heating in the pipeline:

Transient sensitivity < Equilibrium sensitivity.

Other forcings not considered:

Aerosols

Estimated climate sensitivity too low:

Sensitivity < IPCC estimates

Forcing-response model does not apply.

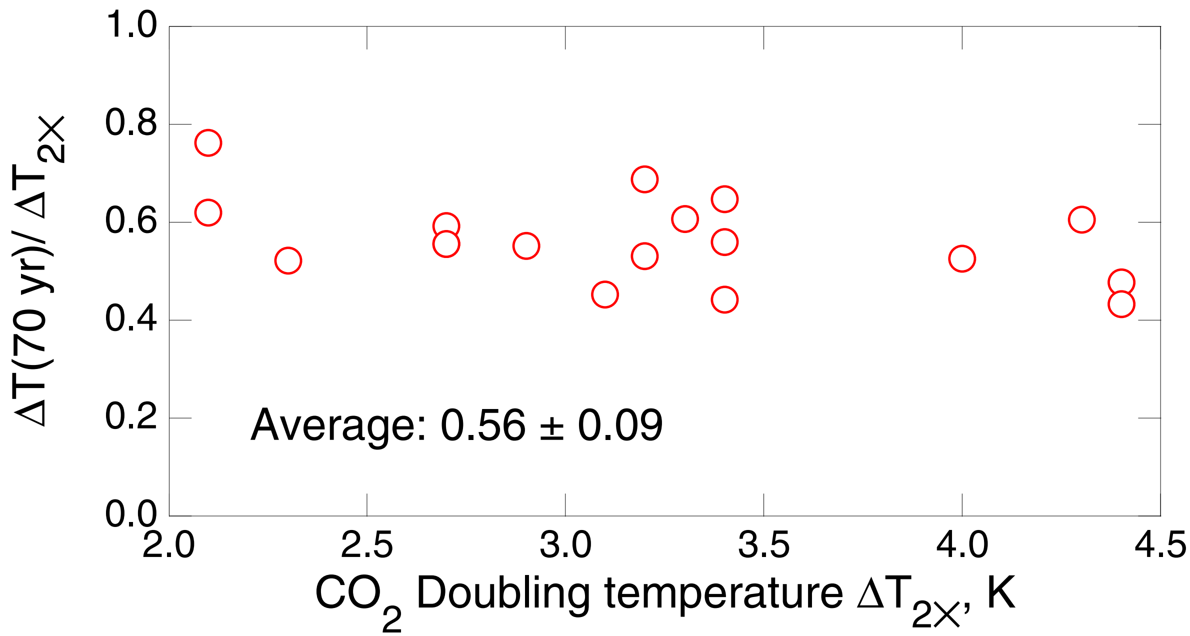
Any or all of the above.

HEATING IN THE PIPELINE

What do climate models tell us?

Transient sensitivity ΔT(70 yr) is increase in global mean temperature at year 70 while increasing CO_2 at 1% per year, compounded.

Compare to equilibrium temperature increase for doubled CO_2, $\Delta T_{2\times}$.



Heating in the pipeline might account for a ***factor of 2*** in observed temperature increase < expected.

KEY APPROACHES TO DETERMINING CLIMATE SENSITIVITY

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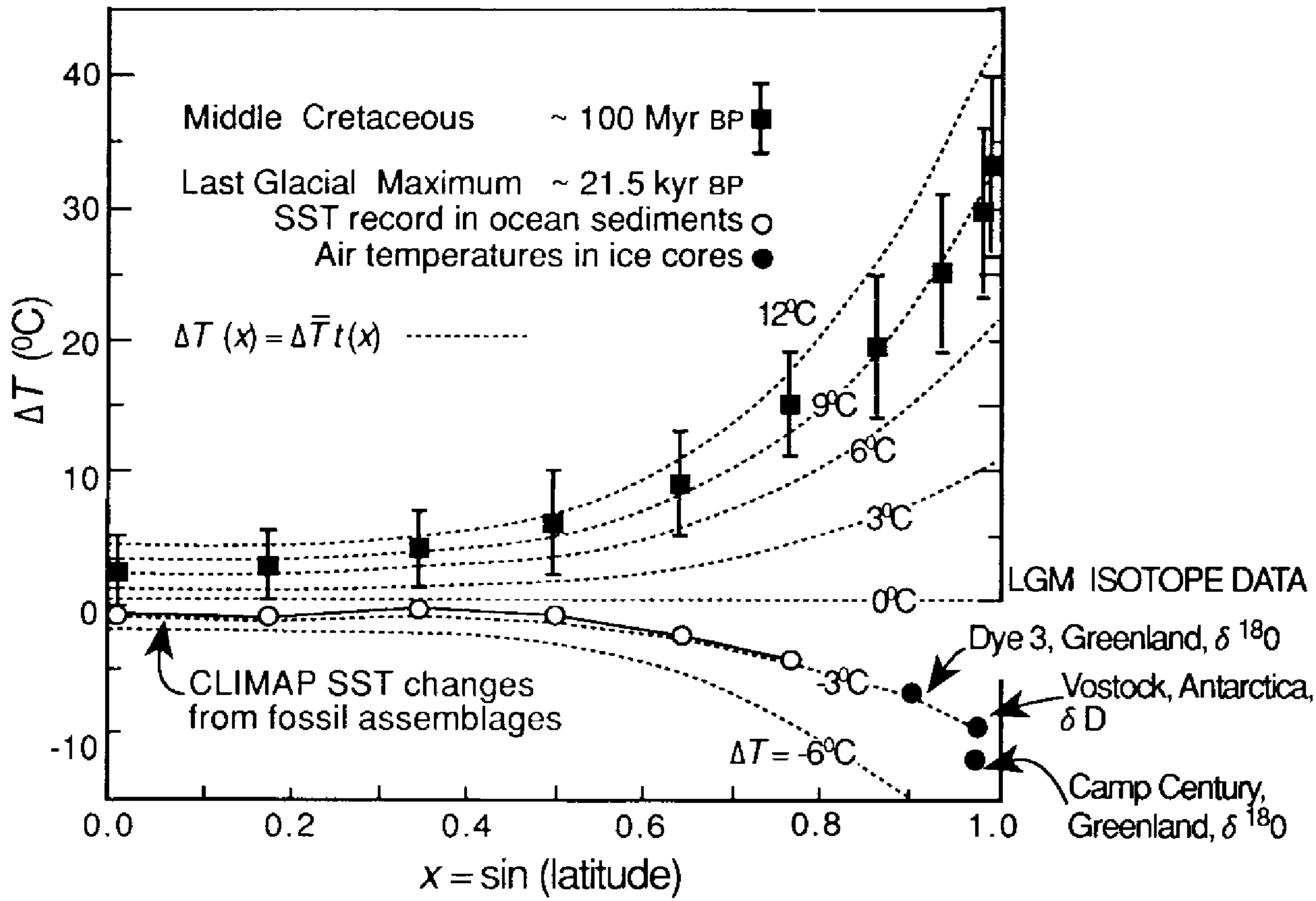
- ***Paleoclimate studies***: Forcing and response over time scales from millennial to millions of years.

GLOBAL MEAN TEMPERATURE FROM PALEO DATA



Hoffert & Covey, Nature, 1992

Last Glacial Maximum: ΔT = -3 K; Middle Cretaceous, ΔT = +9 K.

CLIMATE SENSITIVITY FROM PALEO DATA

Component	Last Glacial Maximum	Middle Cretaceous
Forcing, W m^{-2}	Value ± 1 σ	Value ± 1 σ
Sun	0.0 ± 0.2	-1.2 ± 0.2
Albedo	-3.0 ± 0.5	5.8 ± 0.9
Greenhouse	-2.8 ± 0.3	11.1 ± 6.7
Aerosol	-0.9 ± 0.7	
Total ΔF, W m^{-2}	-6.7 ± 0.9	15.7 ± 6.8
ΔT, K	-3.0 ± 0.5	9.0 ± 2.0
S, K/(W m^{-2})	0.45 ± 0.11	0.57 ± 0.27
$\Delta T_{2\times}$, K ($F_{2\times} = 4.4$ W m^{-2})	2.0 ± 0.5	2.5 ± 1.2

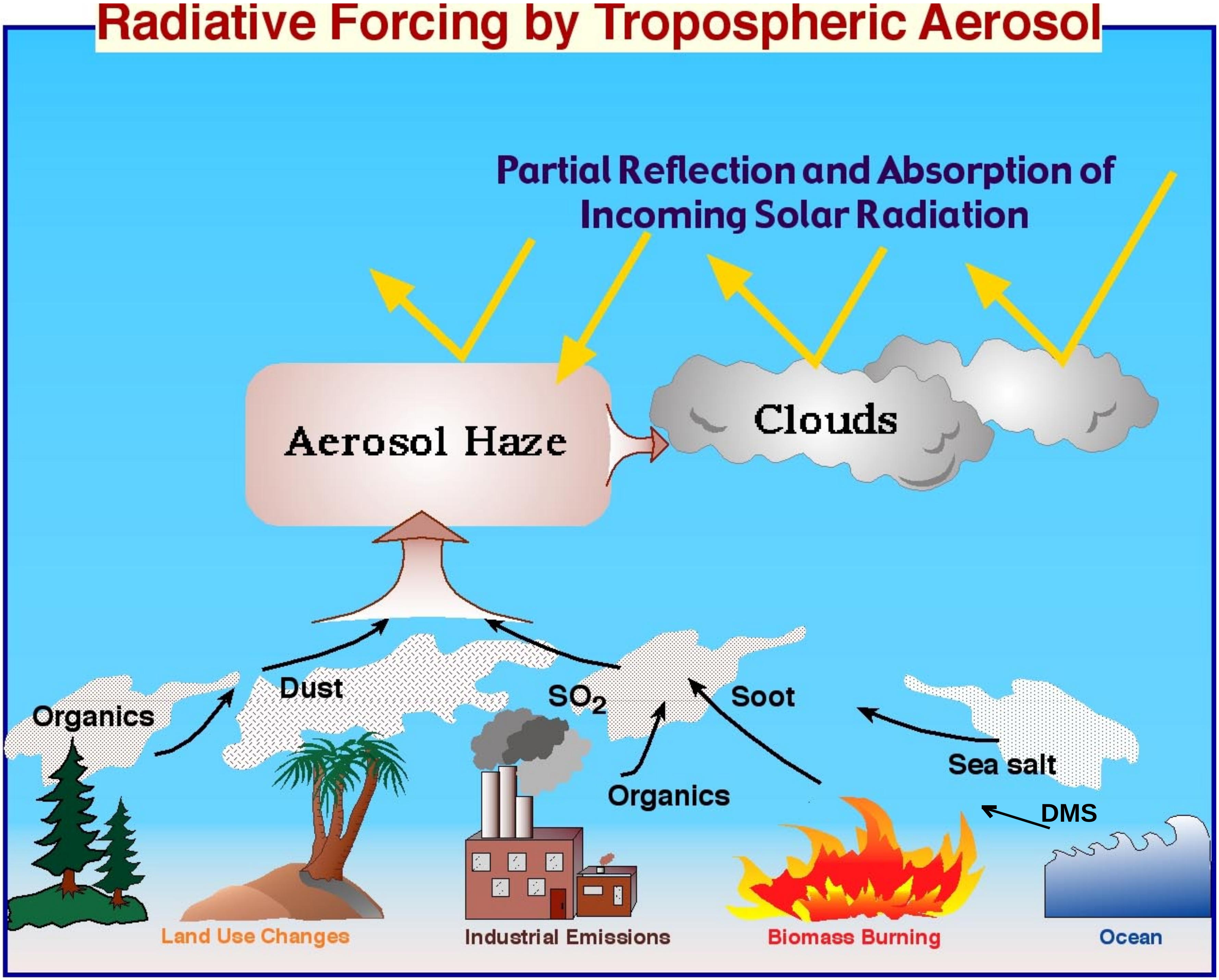
Hoffert & Covey, Nature, 1992

Best estimate $S = 0.51 \pm 0.2$ K/(W m^{-2}); $\Delta T_{2\times} = 2.3 \pm 0.9$ K (1 σ).

KEY APPROACHES TO DETERMINING CLIMATE SENSITIVITY

- ***Paleoclimate studies***: Forcing and response over time scales from millennial to millions of years.

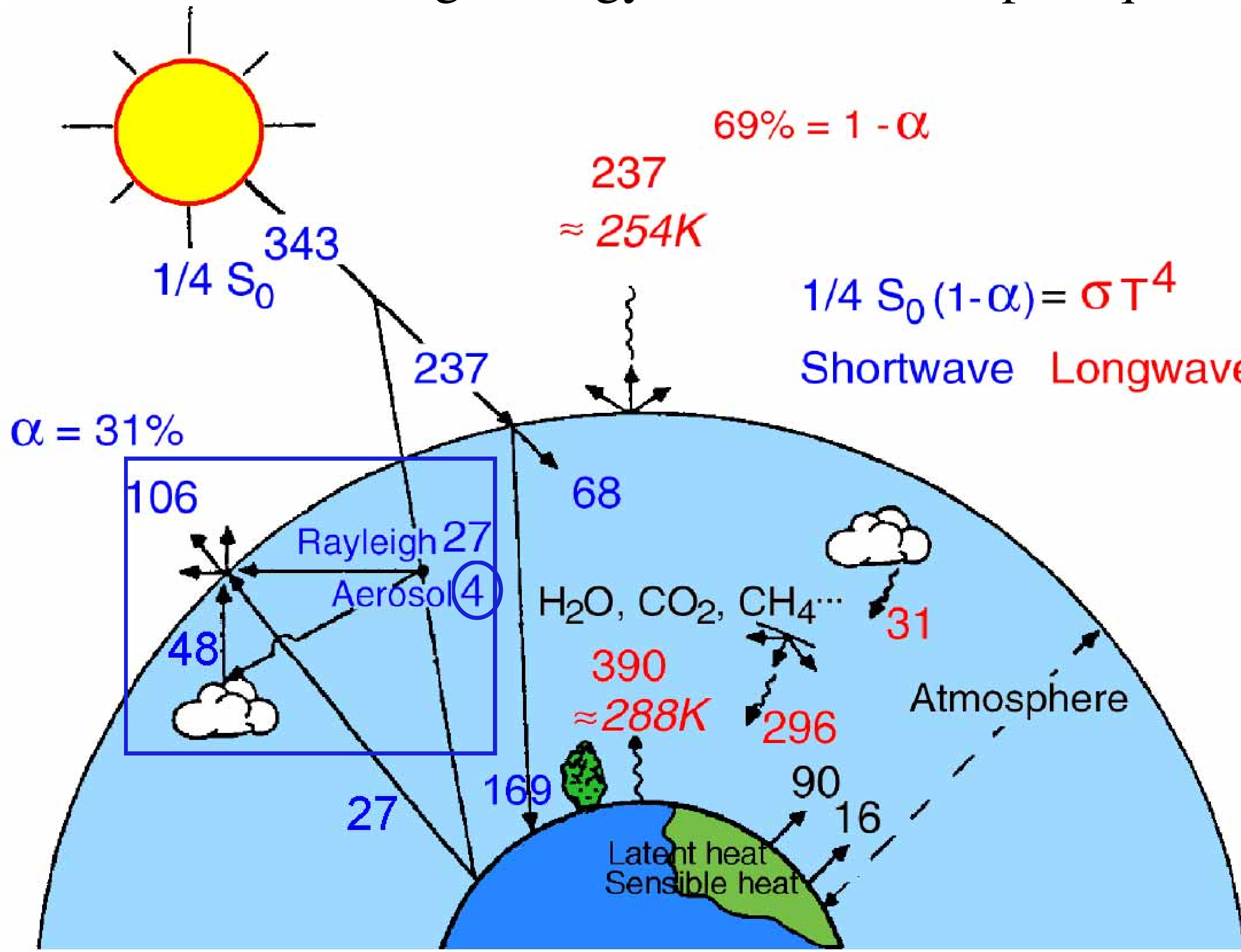
- ***Empirical***: Forcing and response over the instrumental record.



Radiative Forcing by Tropospheric Aerosol
Partial Reflection and Absorption of Incoming Solar Radiation
Aerosol Haze
Clouds
Organics
Dust
SO2
Soot
Organics
Sea salt
DMS
Land Use Changes
Industrial Emissions
Biomass Burning
Ocean

GLOBAL ENERGY BALANCE

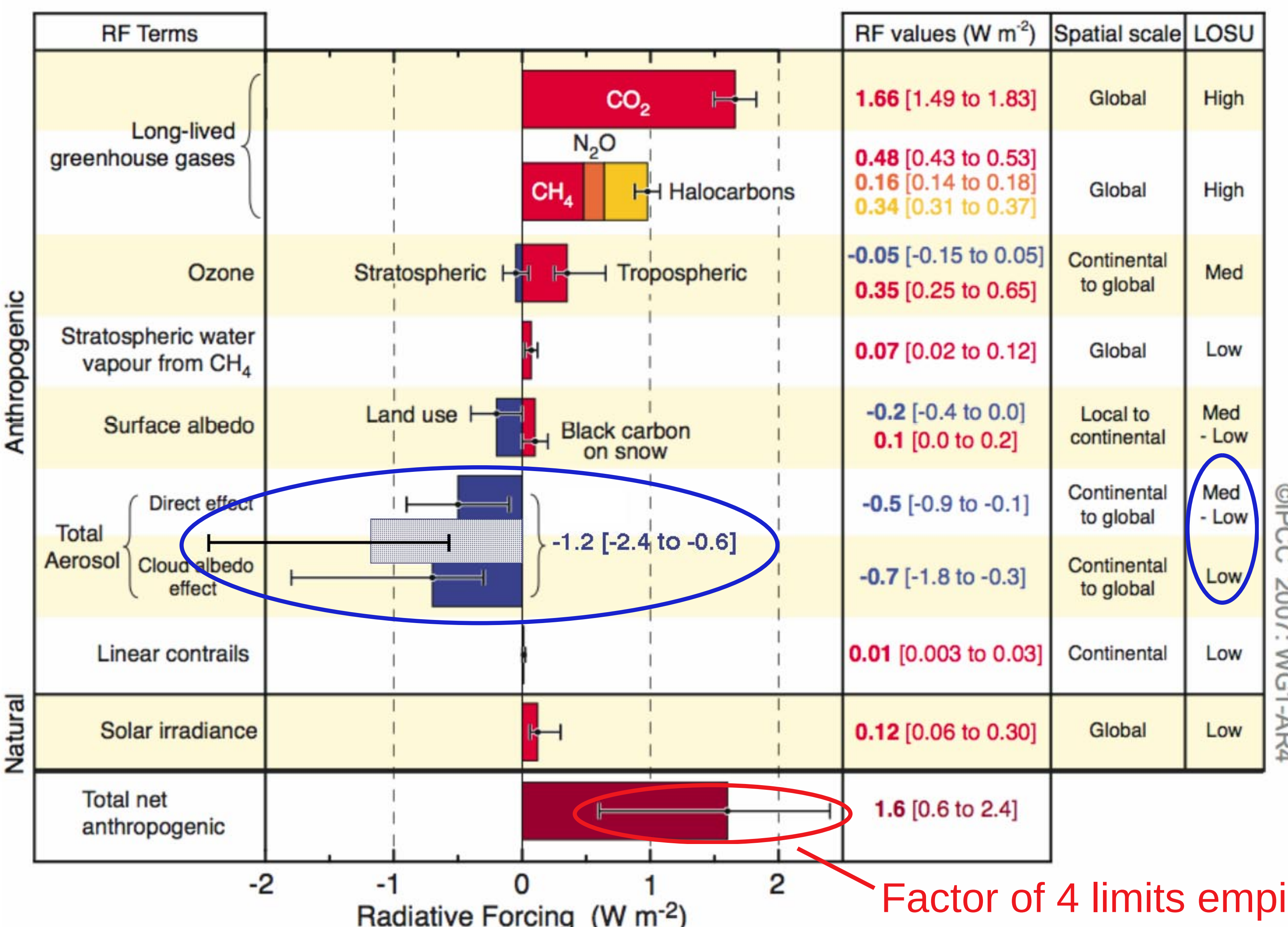
Global and annual average energy fluxes in watts per square meter

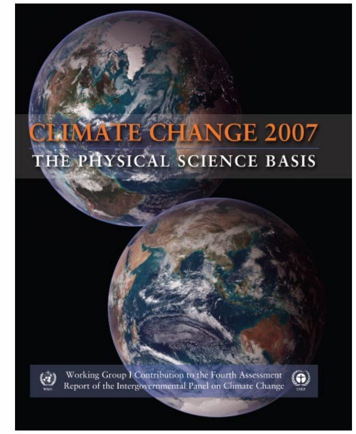


Schwartz, 1996, modified from Ramanathan, 1987

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

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





Factor of 4 limits empirical inferences and model evaluation.

LOSU denotes level of scientific understanding.

AEROSOLS
THE “MONKEY WRENCH” OF FORCING





Atmospheric Aerosol Properties and Climate Impacts

U.S. Climate Change Science Program

Synthesis and Assessment Product 2.3

January 2009

EMPIRICAL DETERMINATION OF CLIMATE SENSITIVITY OVER INDUSTRIAL PERIOD

Sensitivity is temperature change upon forcing accounting for transient heat uptake – *modified from Gregory et al. J. Clim. 2002*

$$S = \frac{\Delta T}{\Delta F - (dH/dt)}$$

Evaluated for 1957-1994 vs. 1861-1900 for $\Delta F_{2\times} = 3.71$ W m^{-2}

Symbol	Quantity	Value ± 1σ	Unit
ΔT	Temperature change	0.335 ± 0.017	K
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KEY APPROACHES TO DETERMINING CLIMATE SENSITIVITY

- ***Paleoclimate studies***: Forcing and response over time scales from millennial to millions of years.

- ***Empirical***: Forcing and response over the instrumental record.

- ***Climate modeling***: Understanding the processes that comprise Earth's climate system and representing them in large-scale numerical models.

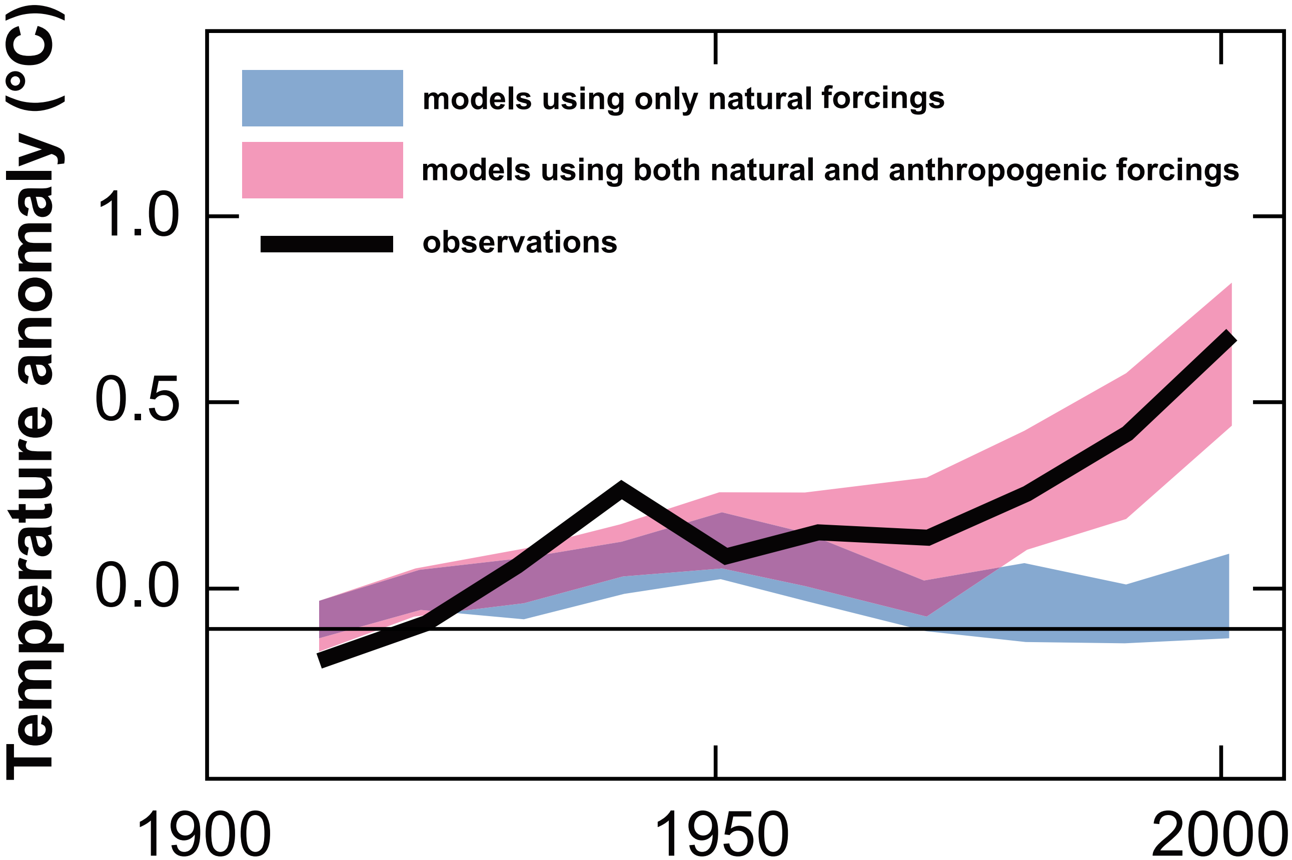
CLIMATE SENSITIVITY ESTIMATES FROM GLOBAL CLIMATE MODELS

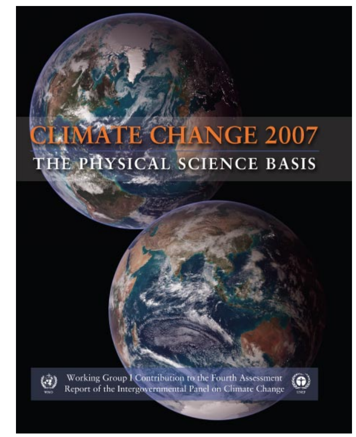
18 Current global climate models – IPCC AR4, 2007

Range of model sensitivities is identical with range of current overall IPCC sensitivity estimate.

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



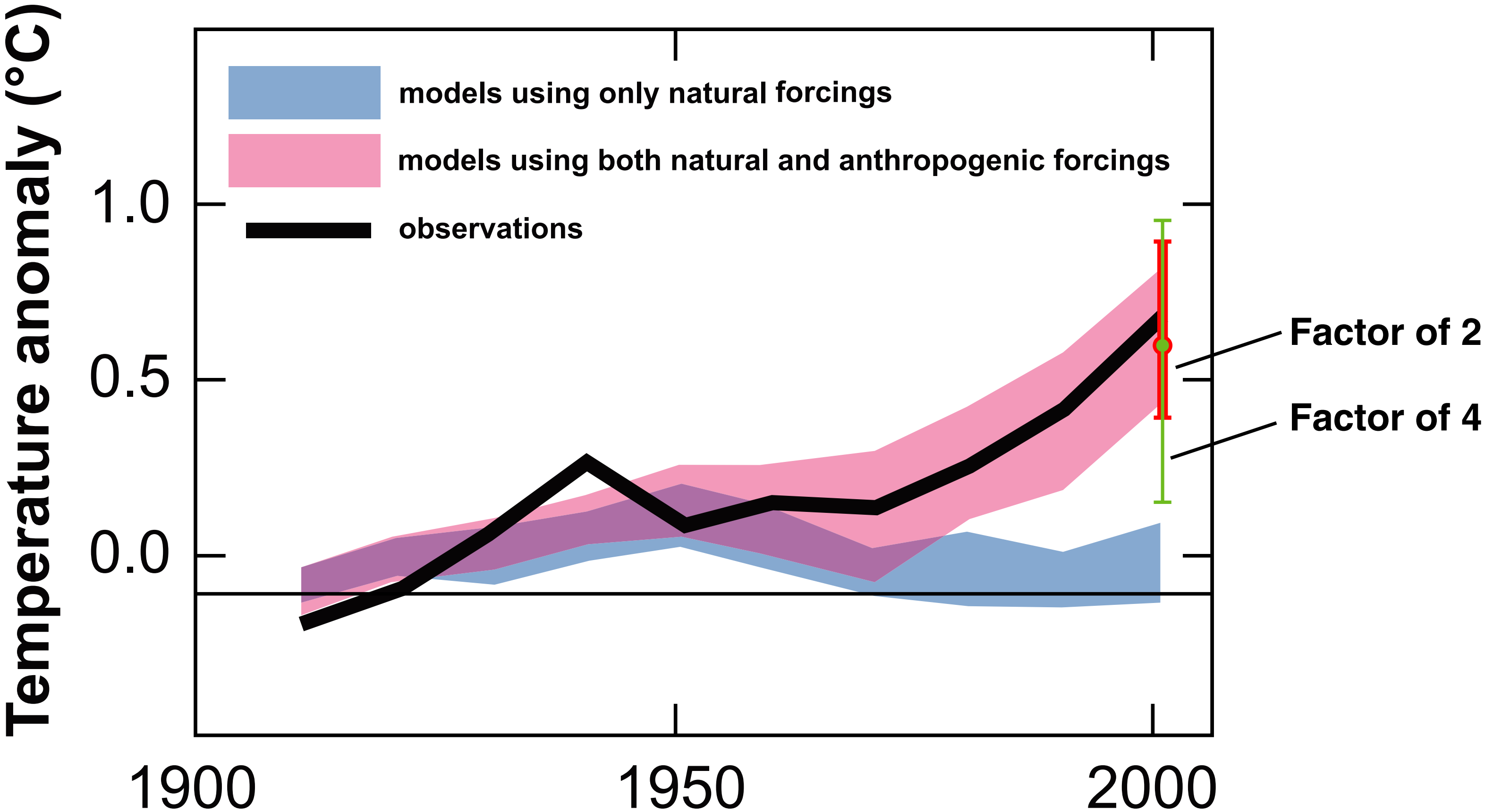


“ Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a ***consistent explanation of the observed temperature record***.

“ These simulations used models with ***different climate sensitivities, rates of ocean heat uptake and magnitudes and types of forcings***.

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



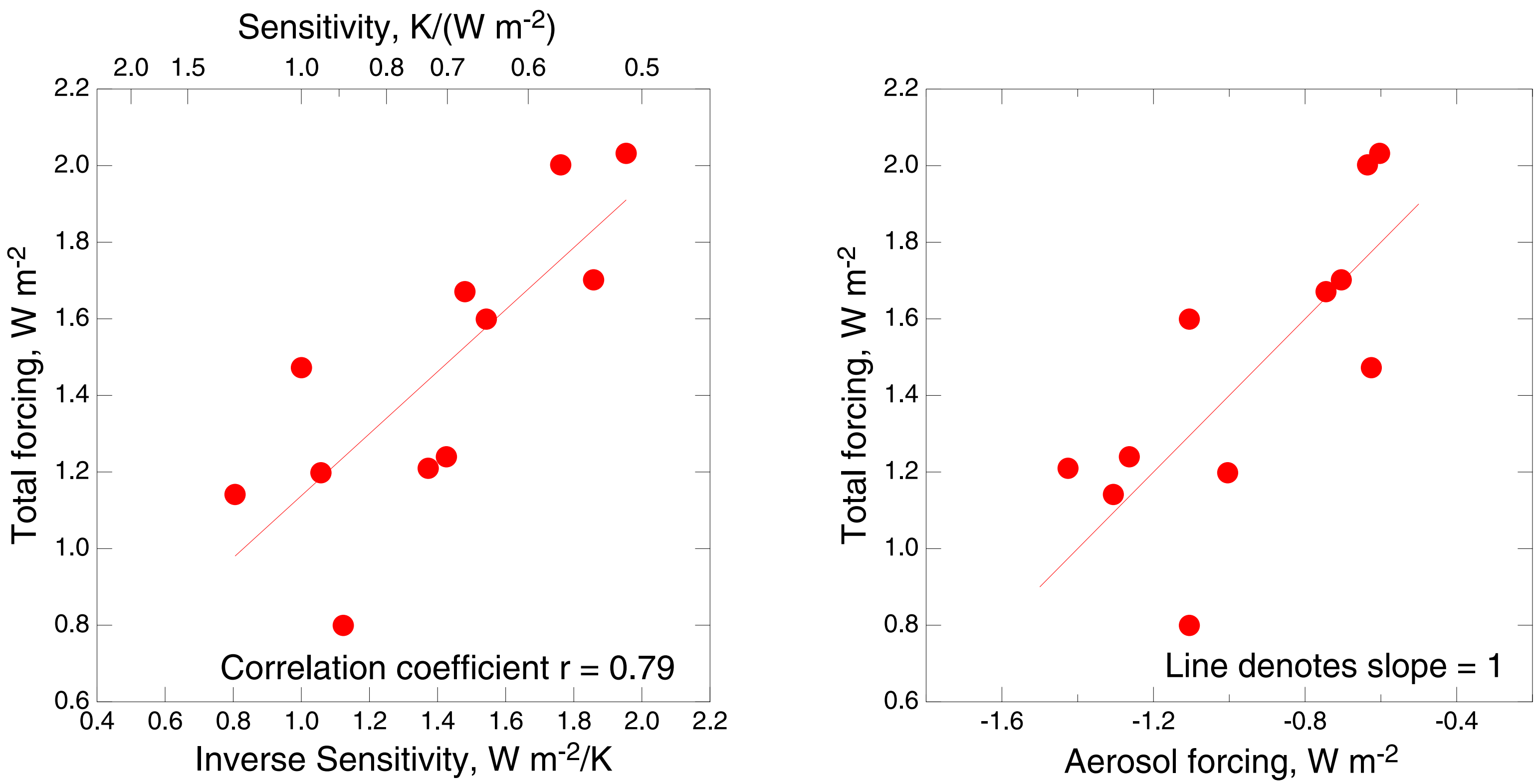
Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007

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 AEROSOL FORCING, TOTAL FORCING, AND SENSITIVITY IN CLIMATE MODELS

Eleven models used in 2007 IPCC analysis



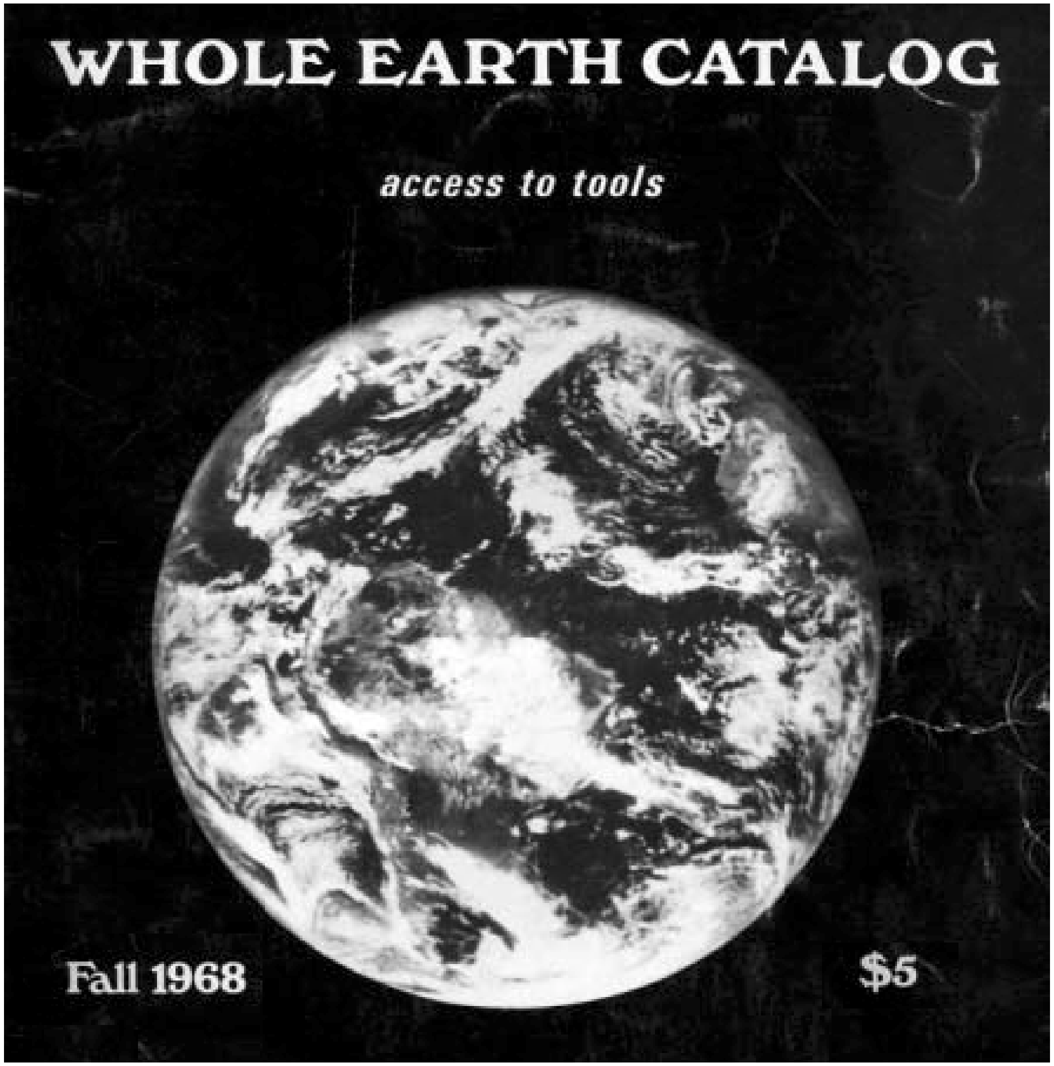
Modified from Kiehl, GRL, 2007

Total forcing was linearly correlated with inverse of model sensitivity.

Climate models with lower sensitivity (higher inverse sensitivity) employed a greater total forcing.

Greater total forcing is due to lower magnitude (less negative) aerosol forcing.

CLIMATE SENSITIVITY FROM WHOLE EARTH ENERGY BALANCE MODELS



ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

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

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_S is solar constant

γ is planetary co-albedo

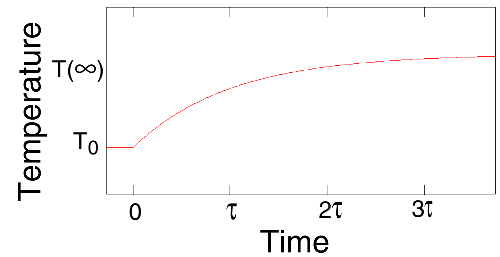
σ is Stefan-Boltzmann constant

ε is effective emissivity

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

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

At new "equilibrium" $\Delta T_S(\infty) = S\Delta F$



S is equilibrium climate sensitivity

$$S = \frac{T_0}{\gamma_0 J_S} \frac{1}{\left(1 - \frac{1}{4}\frac{d\ln\gamma}{d\ln T}\bigg|_0 + \frac{1}{4}\frac{d\ln\varepsilon}{d\ln T}\bigg|_0\right)} \quad \mathrm{K/(W\ m^{-2})}$$

If γ and ε are constant (***no feedbacks***),

$$S = \frac{T_0}{\gamma_0 J_S}$$

Stefan-Boltzmann sensitivity, $S_{SB} = 0.30\ \mathrm{K/(W\ m^{-2})}$; $\Delta T_{2\times} = 1.1\ \mathrm{K}$

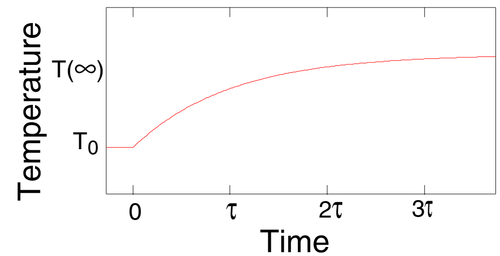
f is feedback *factor*

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

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

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

At "equilibrium" $\Delta T_s(\infty) = S\Delta F$



S is equilibrium climate sensitivity $S = \frac{T_0}{\gamma_0 J_S} f = S_{SB} f$ Stefan-Boltzmann senstivity times feedback factor

Time dependence: $\Delta T_s(t) = S\Delta F(1 - e^{-t/\tau})$

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

One equation in three unknowns!

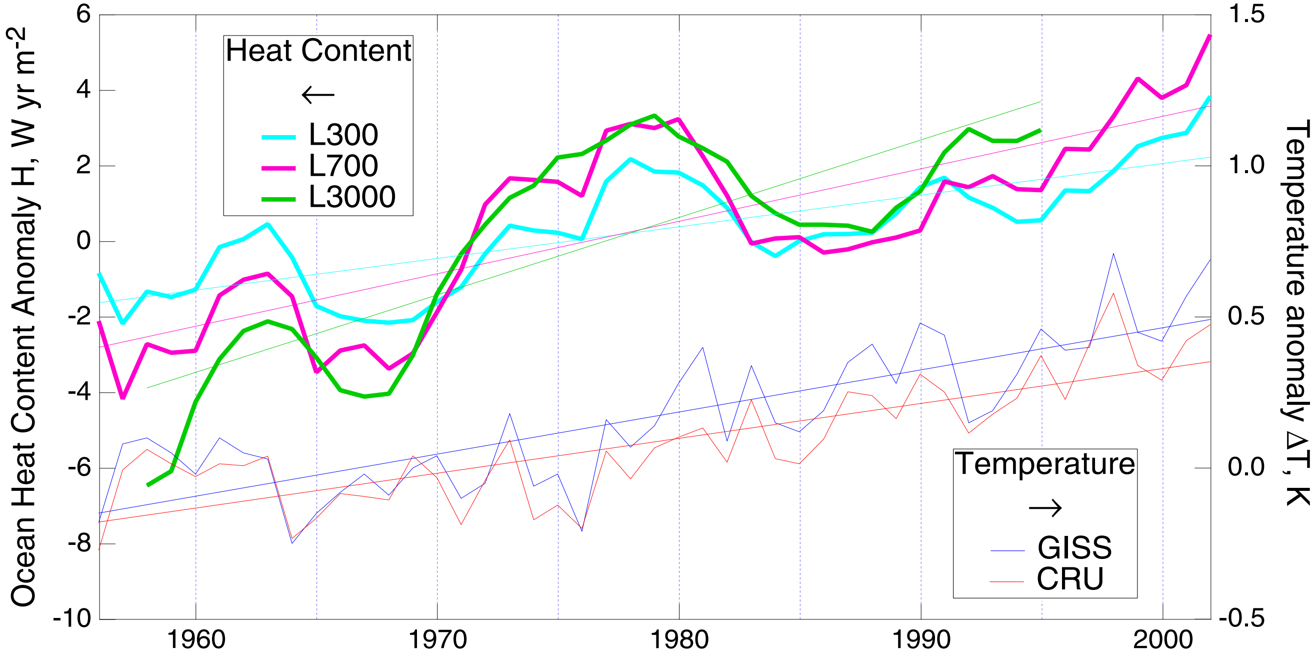
Approach: Determine *C* and τ from measurements; calculate sensitivity *S*.

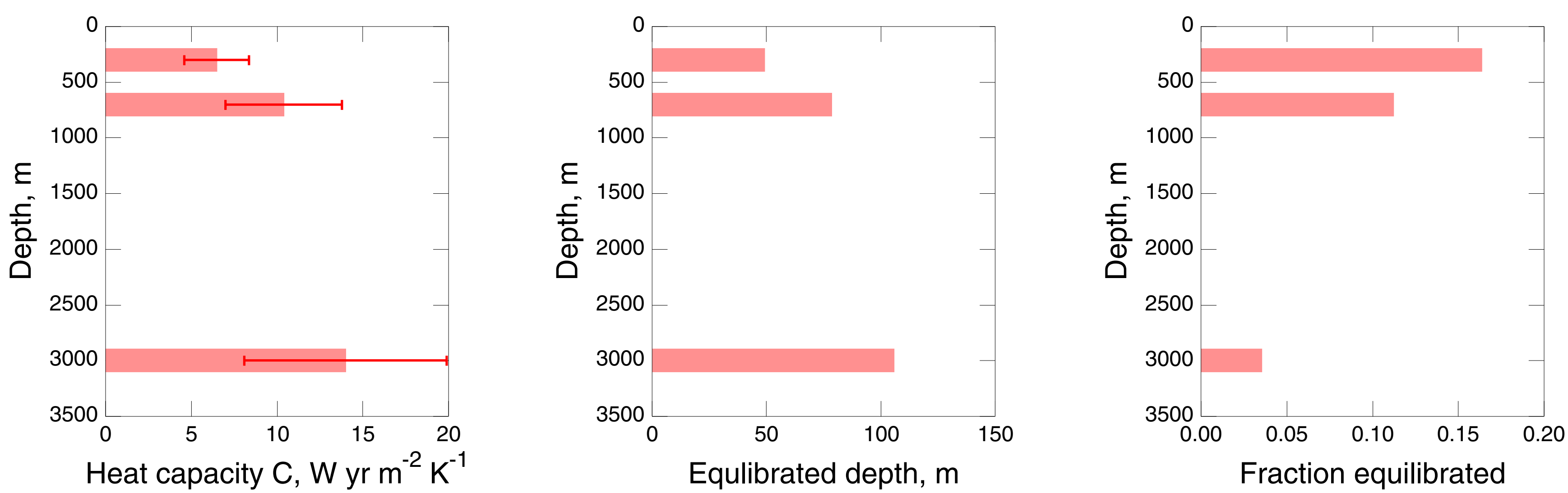
EMPIRICAL DETERMINATION OF OCEAN HEAT CAPACITY

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

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

Surface temperature T_S: GISS, CRU





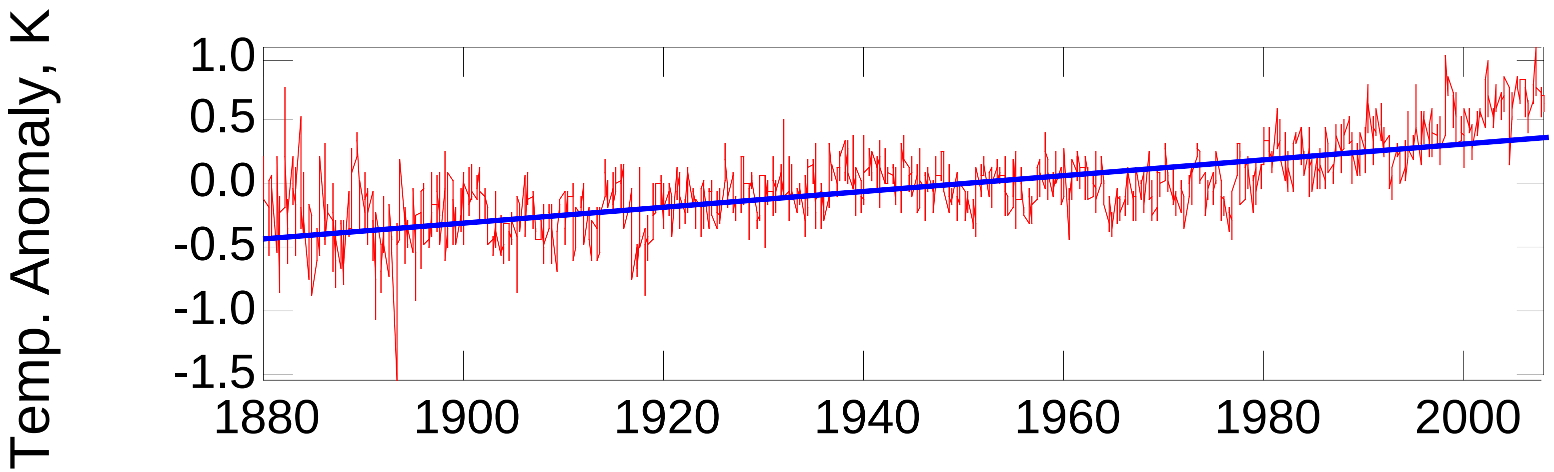
- ~50% of heat capacity is between surface and 300 m.
- Other heat sinks raise global heat capacity to 17 ± 7 W yr m^{-2} K^{-1}.

Schwartz, JGR, 2007

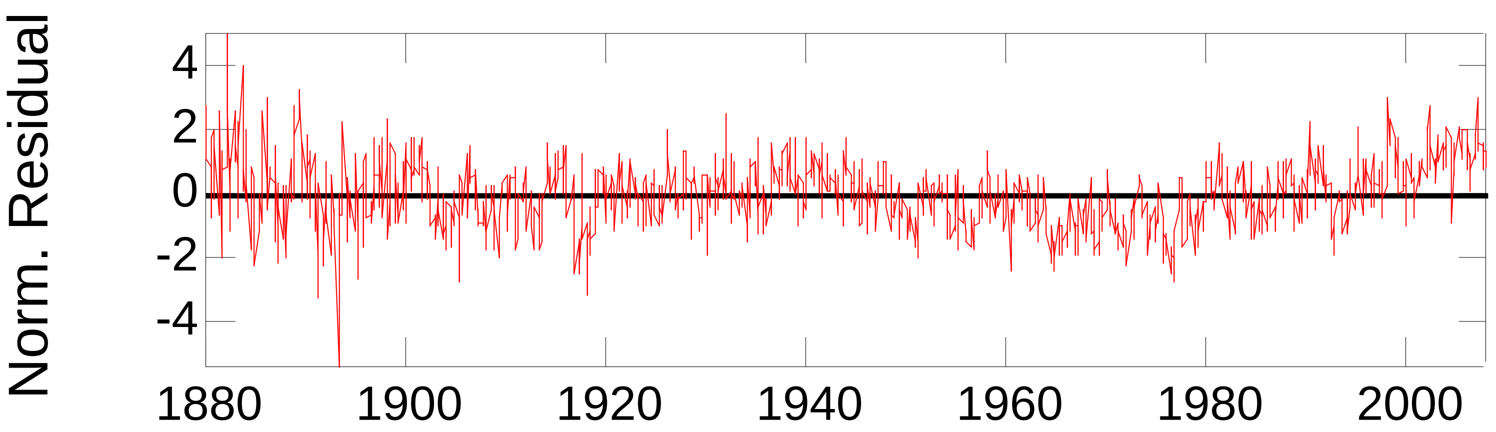
TIME CONSTANT OF EARTH'S CLIMATE SYSTEM

Determination from autocorrelation of time series

Input: Monthly global-mean surface temperature anomaly T_s



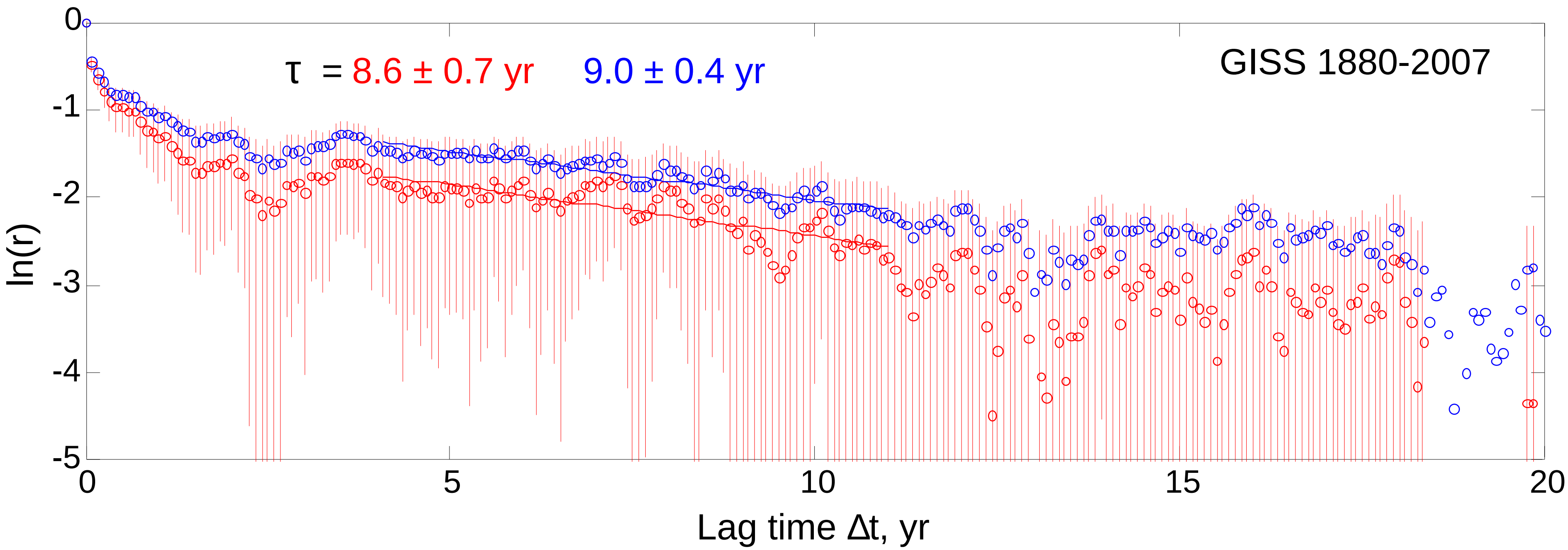
Remove long term trend; plot the residuals:



TIME CONSTANT OF EARTH'S CLIMATE SYSTEM
Determination from autocorrelation of time series (*cont'd*)

Evaluate ***climate system time constant*** as $\tau = (d \ln r(\Delta t)/d\, \Delta t)^{-1}$

Correct for short duration of time series.



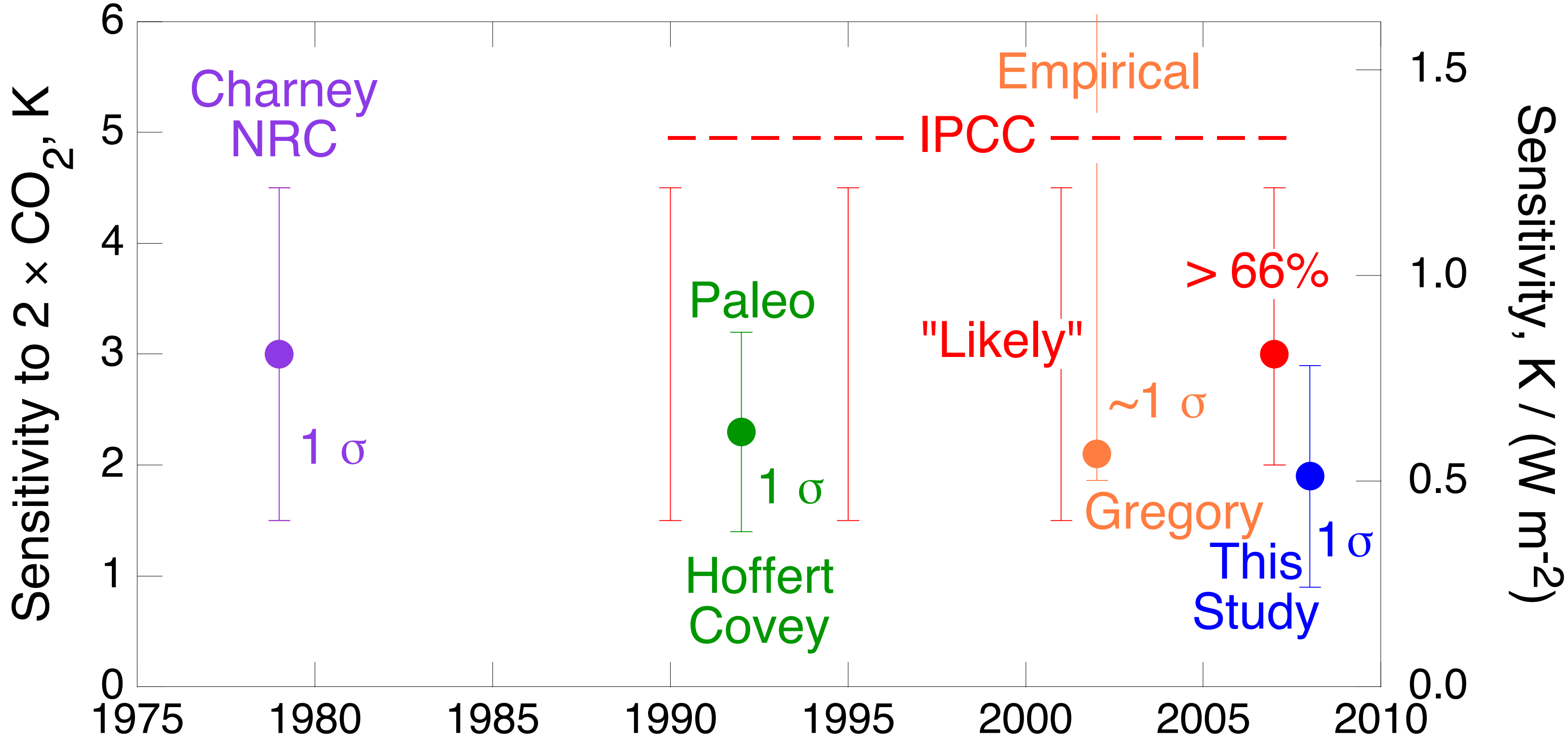
Summary (multiple data sets):

Climate system time constant is 8.5 ± 2.5 years

Schwartz, JGR, 2008

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

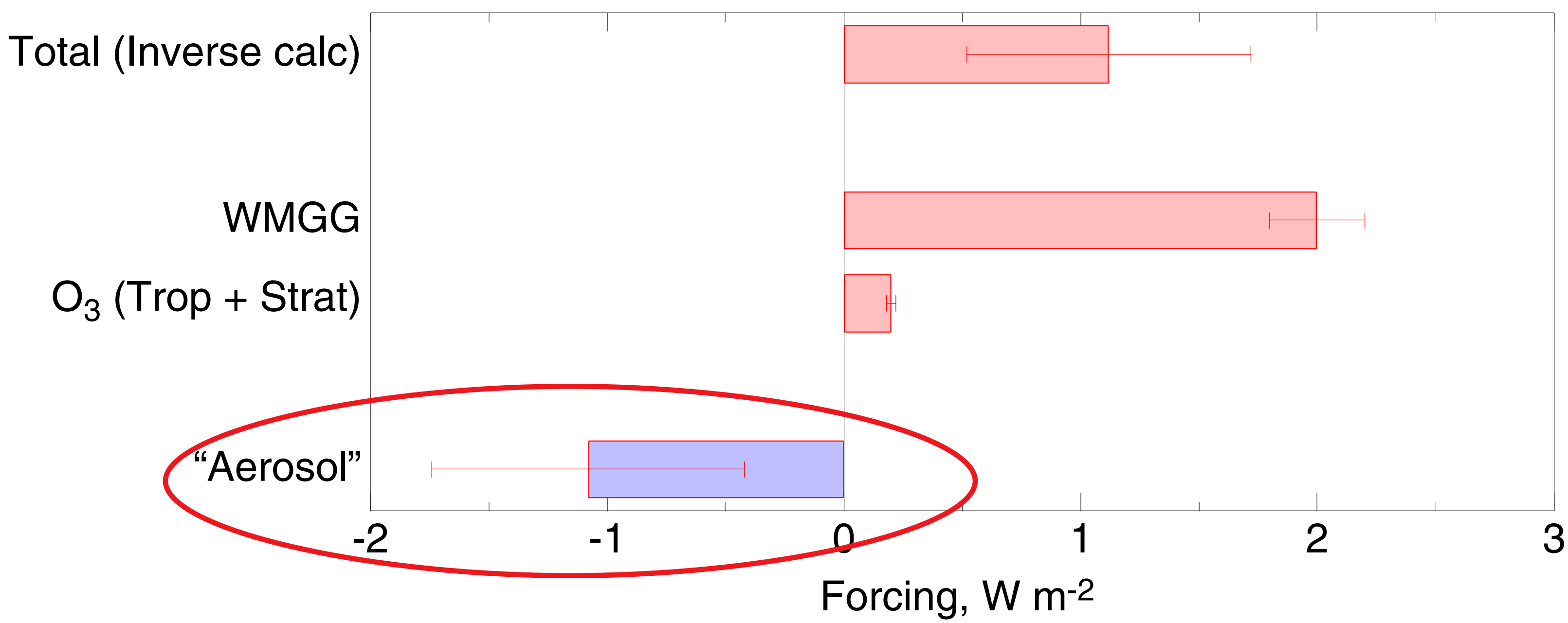
Estimates of central value and uncertainty range from specific approaches and major national and international assessments



Sensitivity obtained in this study overlaps range from climate models, paleo, empirical; seems to rule out $\Delta T_{2\times} \gtrsim 3$ K.

INVERSE CALCULATION OF "AEROSOL" FORCING OVER TWENTIETH CENTURY

"Aerosol" forcing = Total forcing – GHG forcing



Total forcing remains uncertain to a factor of 3.

"Aerosol" forcing, calculated as residual, is presumably dominated by aerosols.

"Aerosol" forcing is substantial, with large uncertainty.

"Aerosol" forcing could be masking as much as 75% of GHG warming.

EVALUATION OF SENSITIVITY AND FORCINGS

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	**8.5**	**2.5**
Equilibrium climate sensitivity $S = \tau / C$	K/(W m^{-2})	**0.51**	**0.26**
Feedback factor f	–	**1.7**	
Equilibrium temperature increase for $2 \times CO_2$, $\Delta T_{2\times}$	K	**1.9**	**1.0**
Total forcing over the 20th century, $F_{20} = \Delta T_{20} / S$	W m^{-2}	**1.1**	**0.6**
Forcing in 20th century other than GHGs (*mainly aerosols*), $F_{20}^{other} = F_{20} - F_{20}^{ghg}$	W m^{-2}	**-1.1**	**0.7**
Lag in temperature change, ΔT_{lag}	K	**0.05**	

CONCLUDING REMARKS

Traditional approaches to determination of Earth's climate sensitivity yield uncertainty of at least a factor of 3, largely because of uncertainty in aerosol forcing.

The energy balance approach offers a new independent determination of Earth's climate sensitivity that does not depend on knowledge of aerosol forcing.

This approach yields a sensitivity that is at the low end of current estimates and would seem to rule out high sensitivity.

The short time constant, ~ 8.5 years, suggests little heating in the pipeline from time lags.

Aerosols could be masking up to 75% of GHG forcing and warming.

Nothing in the present study should be construed as diminishing the need for strenuous reduction in GHG emissions.

FINAL REMARKS

This study is a first effort on this approach. I would hope that it would be refined by further research.

Would I bet the ranch on this analysis? Of course not.