CONSIDER A SPHERICAL EARTH

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

Stephen E. Schwartz

BROOKHAVEN NATIONAL LABORATORY

Department of Atmospheric Science, Pusan National University
Busan, Republic of Korea
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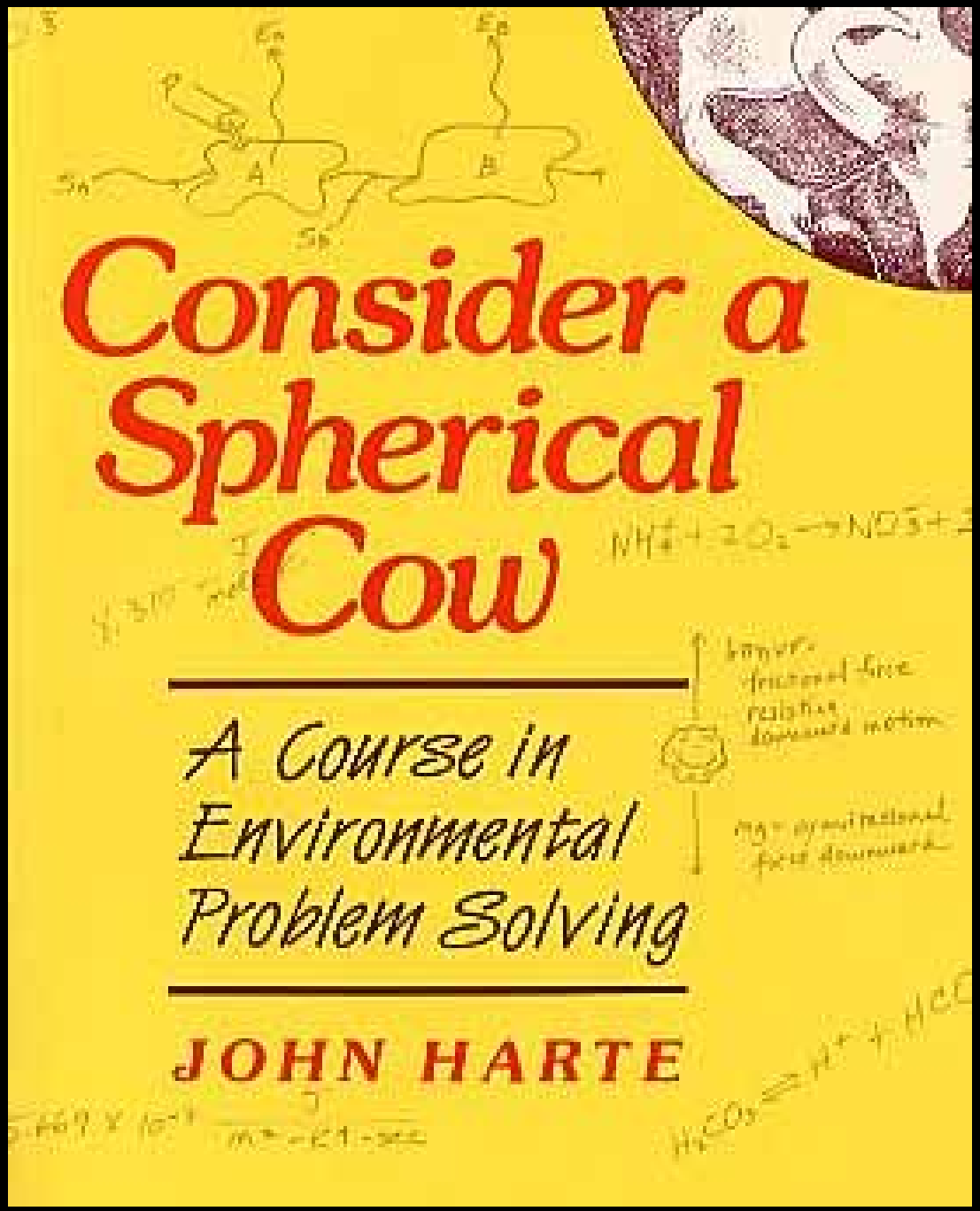
http://www.ecd.bnl.gov/steve


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

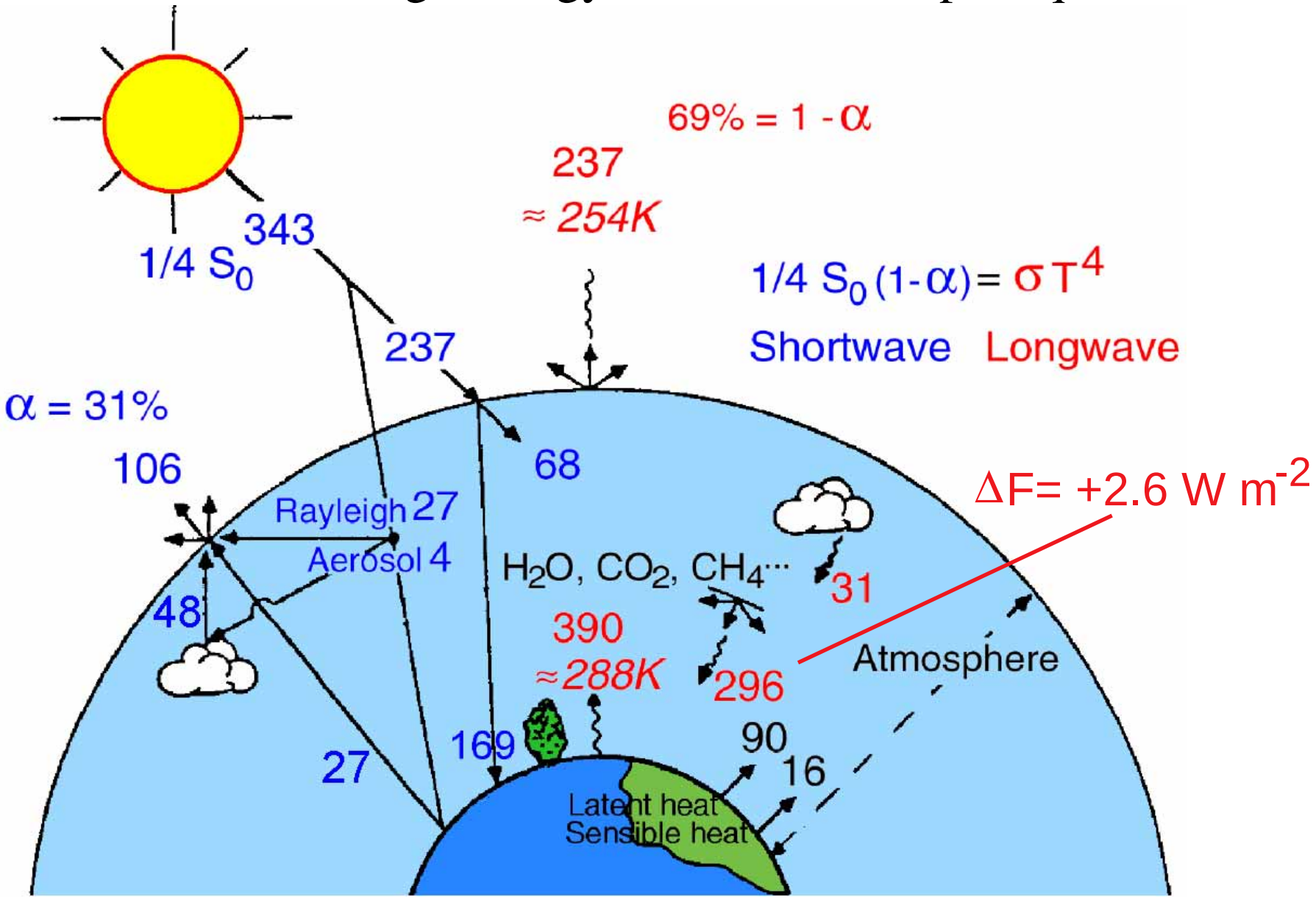
Previous approaches to Earth’s climate sensitivity

Climate sensitivity from whole-earth energy-balance model

Concluding remarks

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

ATMOSPHERIC RADIATION

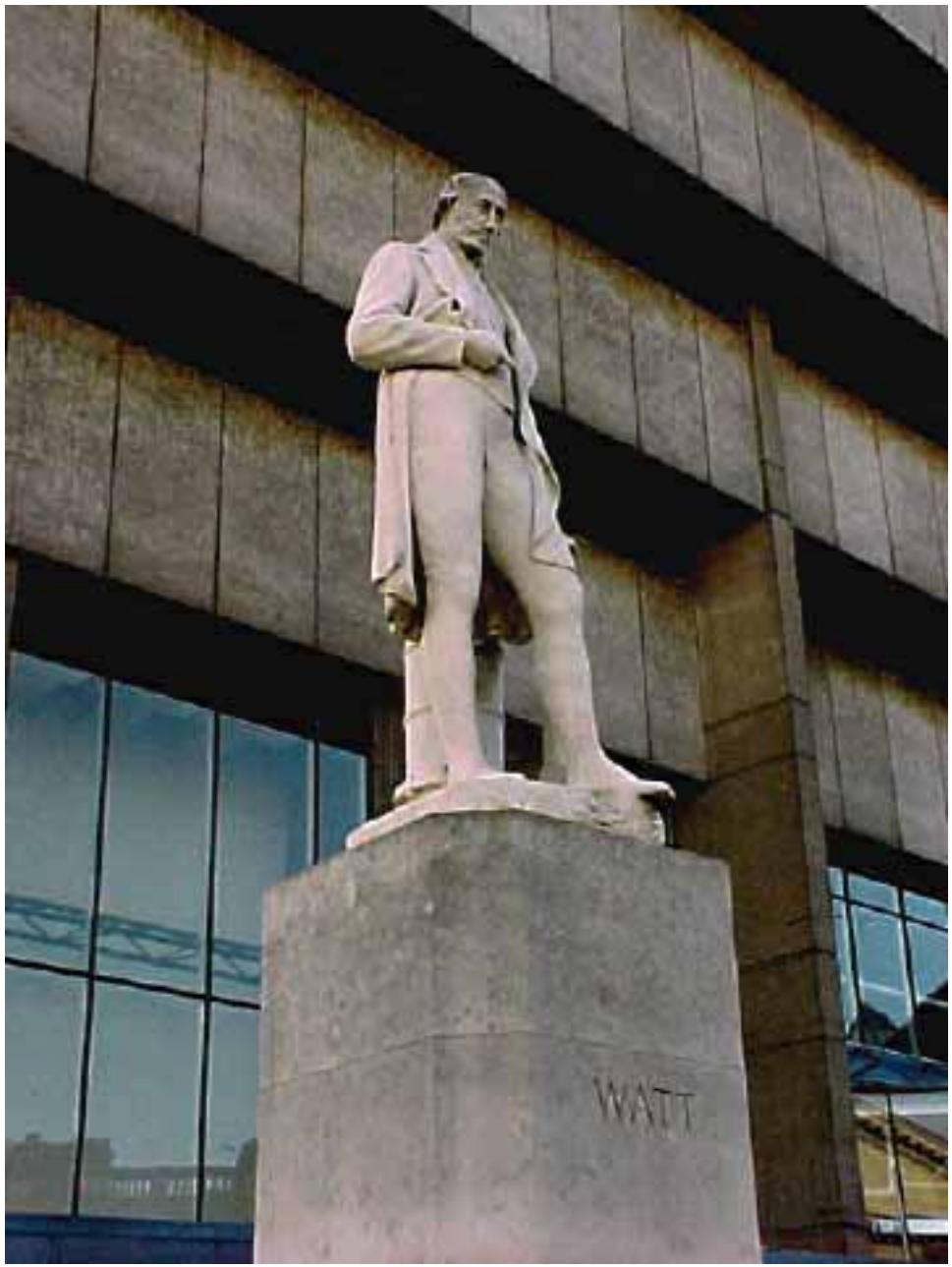
Power per area

Energy per time per area

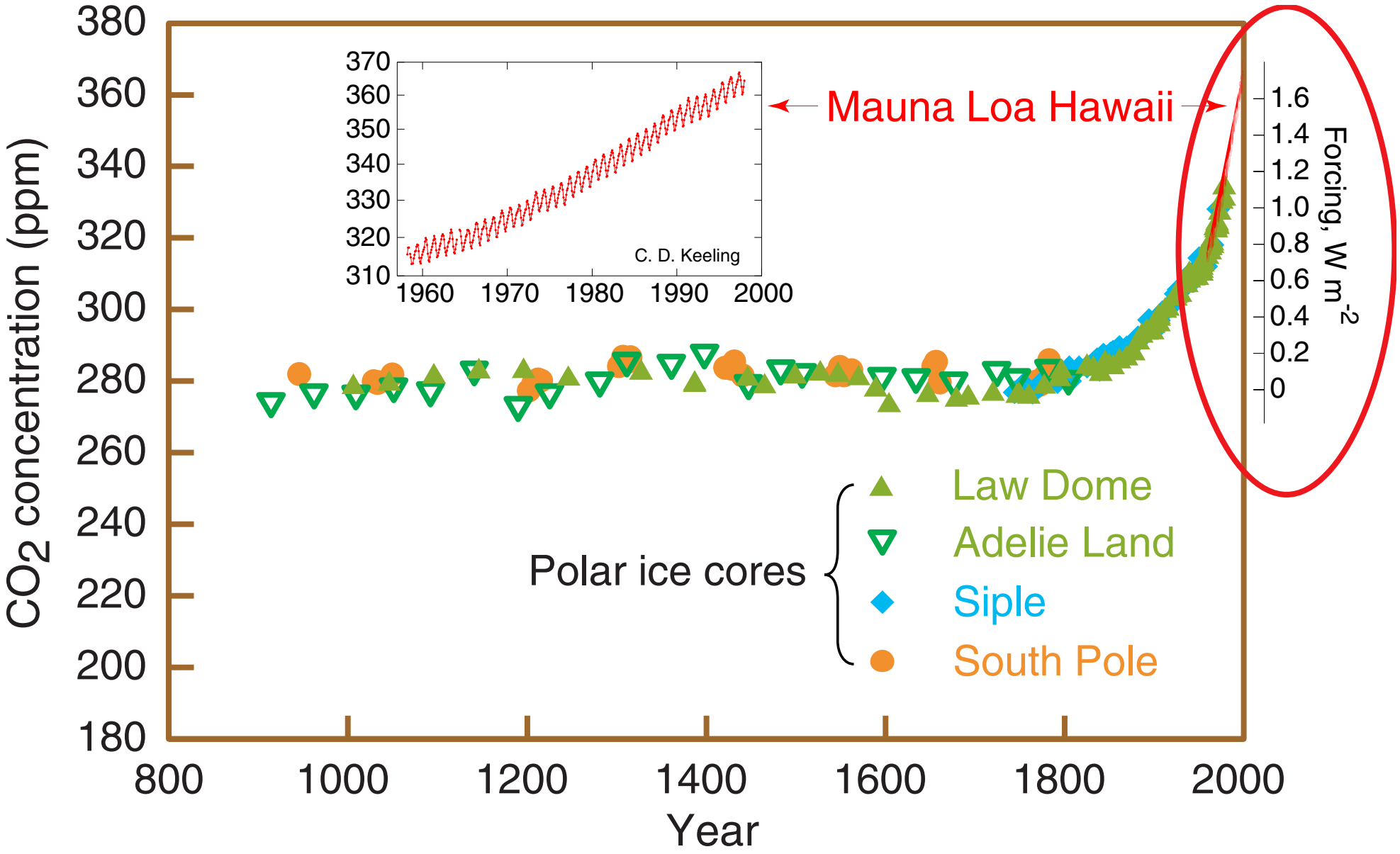
Unit:

Watt per square meter

$W\ m^{-2}$



ATMOSPHERIC CARBON DIOXIDE IS INCREASING



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

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.

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.

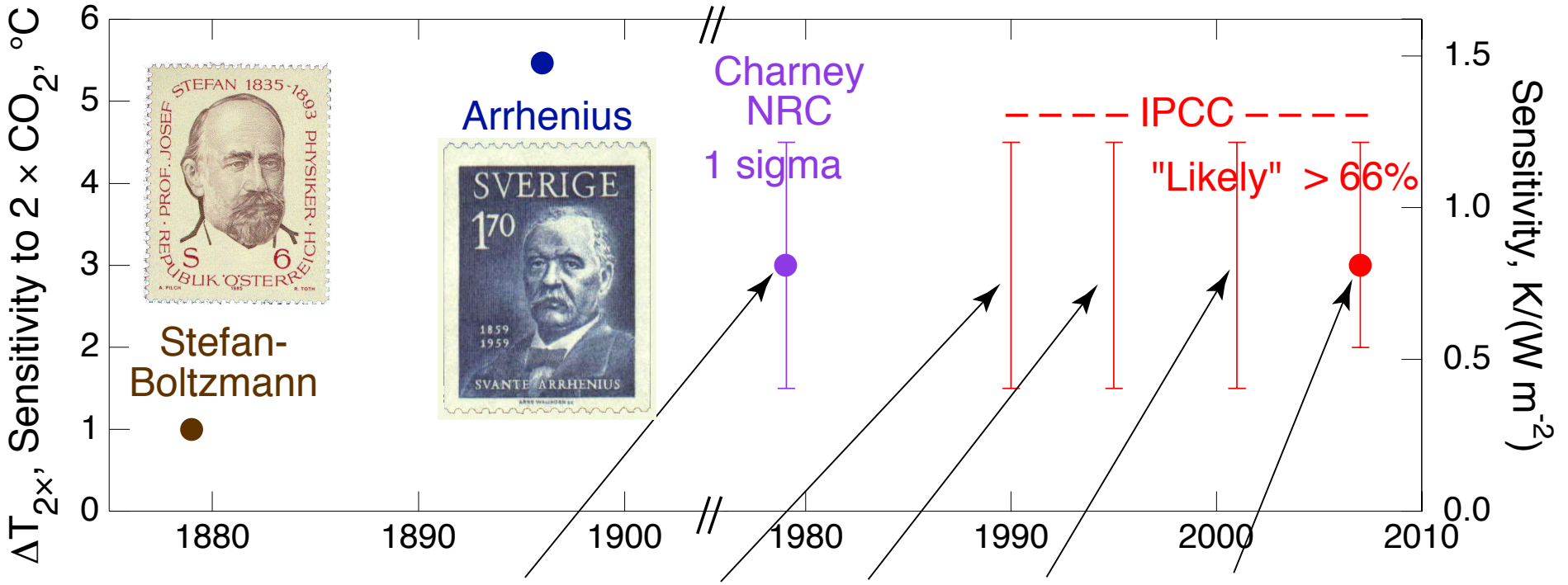
Climate sensitivity is often expressed as the temperature for doubled CO_2 concentration $\Delta T_{2\times}$.

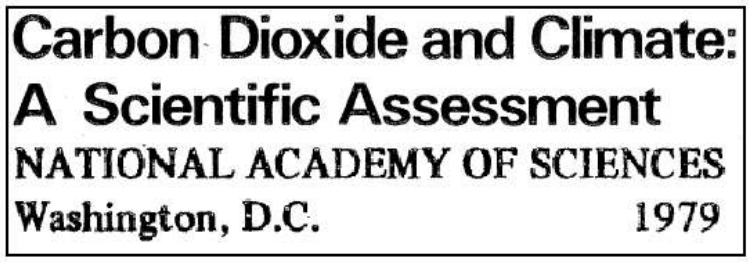
$$\Delta T_{2\times} = S\Delta F_{2\times}$$

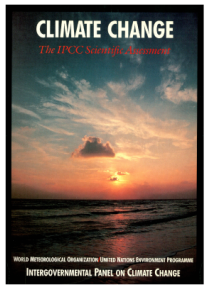
$$\Delta F_{2\times} \approx 3.7 \text{ W m}^{-2}$$

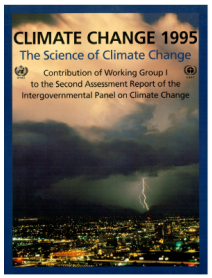
CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

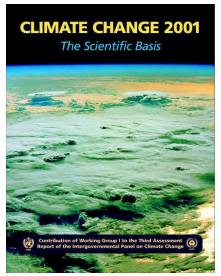
Estimates of central value and uncertainty range from major national and international assessments

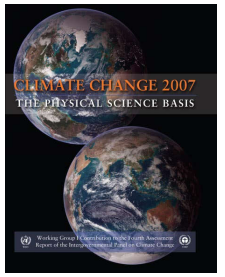












Despite extensive research, climate sensitivity remains ***highly uncertain***.

IMPLICATIONS OF UNCERTAINTY IN CLIMATE SENSITIVITY

Uncertainty in climate sensitivity translates directly into . . .

- Uncertainty in the amount of ***incremental atmospheric*** $\mathbf{CO_2}$ 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 about a factor of 3.

IMPORTANCE OF KNOWLEDGE OF CLIMATE TO INFORMED DECISION MAKING

- The lifetime of incremental atmospheric CO_2 is about 100 years.
- The expected life of a new coal-fired power plant is 50 to 75 years.

Actions taken today will have long-lasting effects.

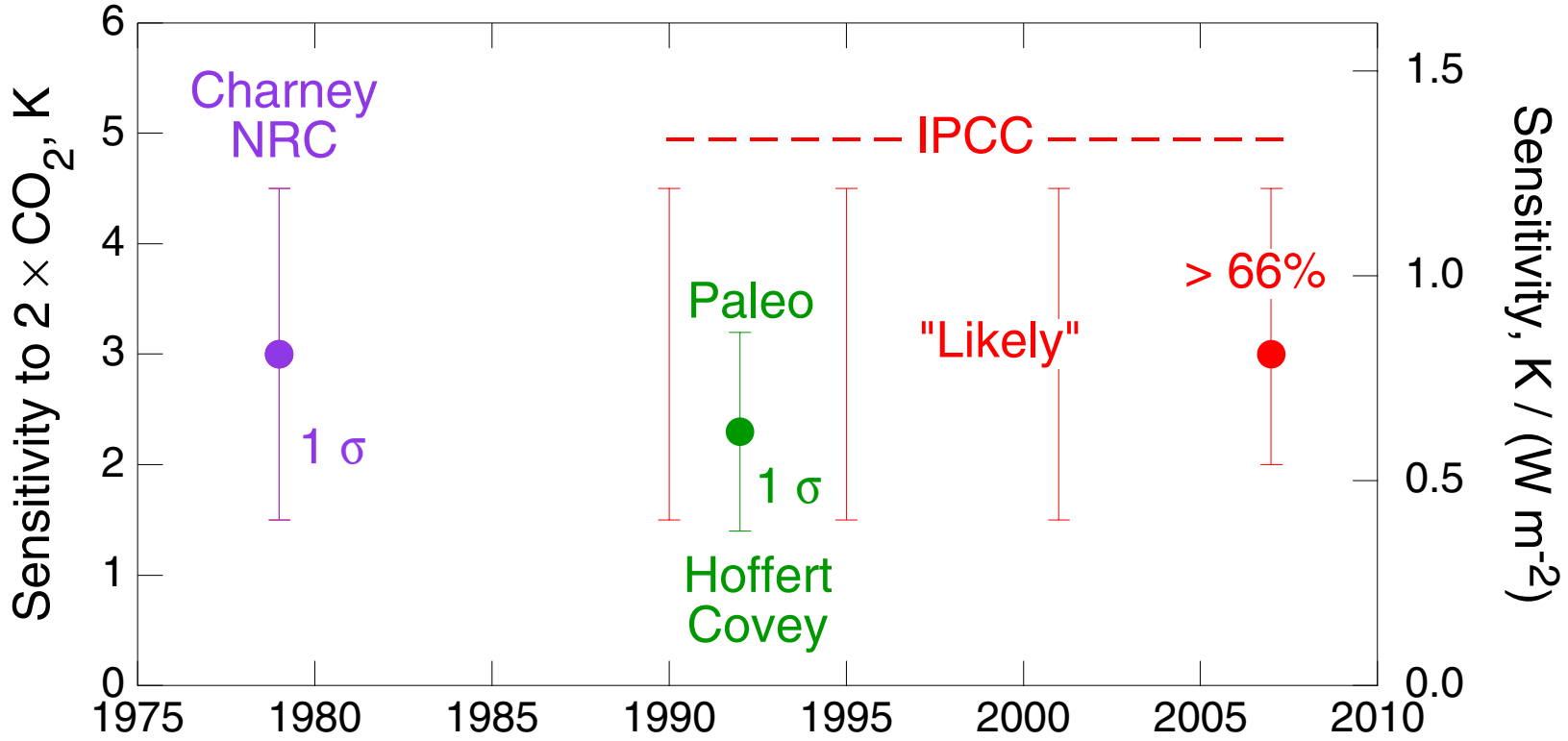
Early knowledge of climate sensitivity can result in huge averted costs.

KEY APPROACHES TO DETERMINING CLIMATE SENSITIVITY

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

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

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



Climate sensitivity from paleo climate has been a major contributor to present assessment of climate sensitivity.

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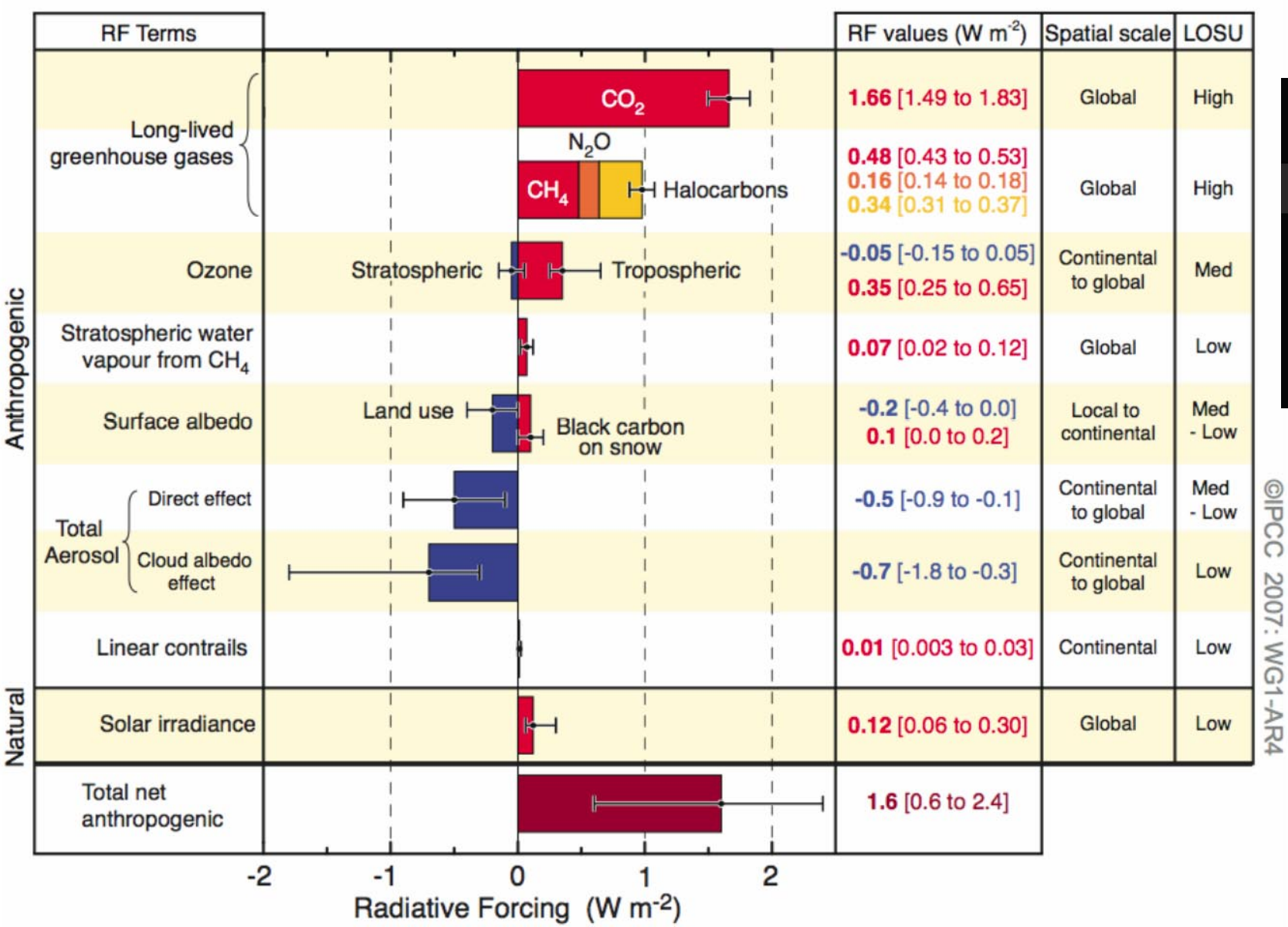
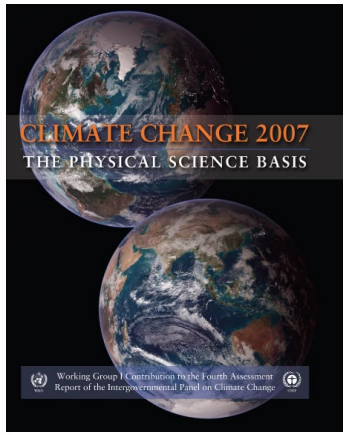
- ***Empirical***: Forcing and response over the instrumental record.

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

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





LOSU denotes level of scientific understanding.

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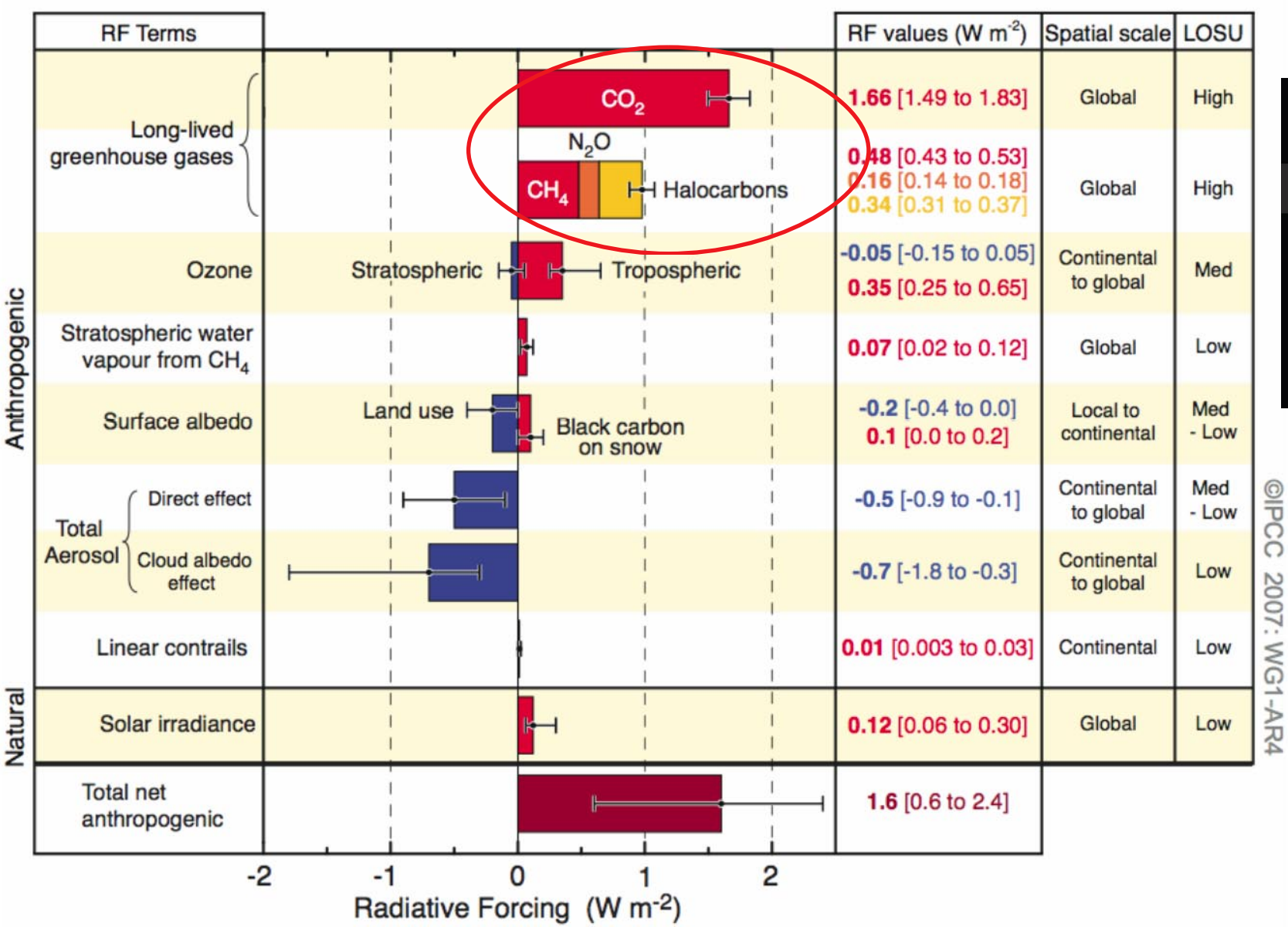

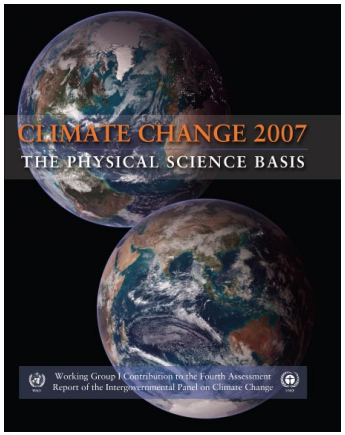

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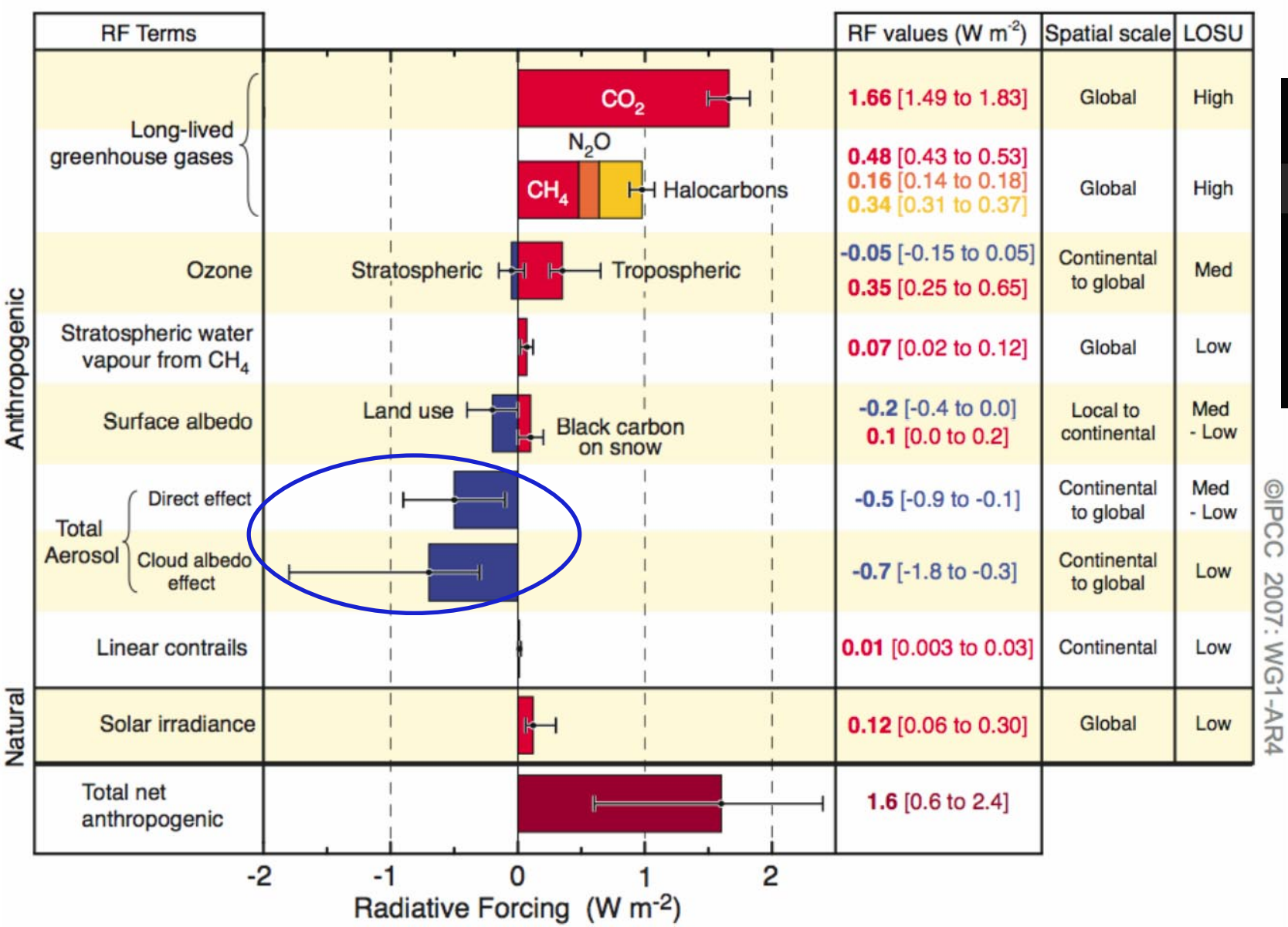

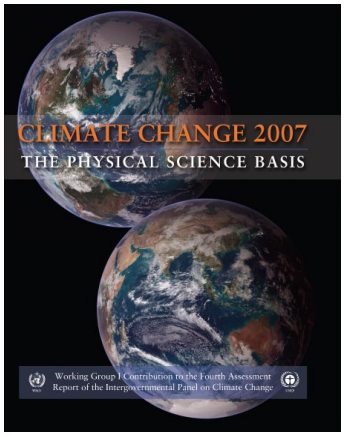

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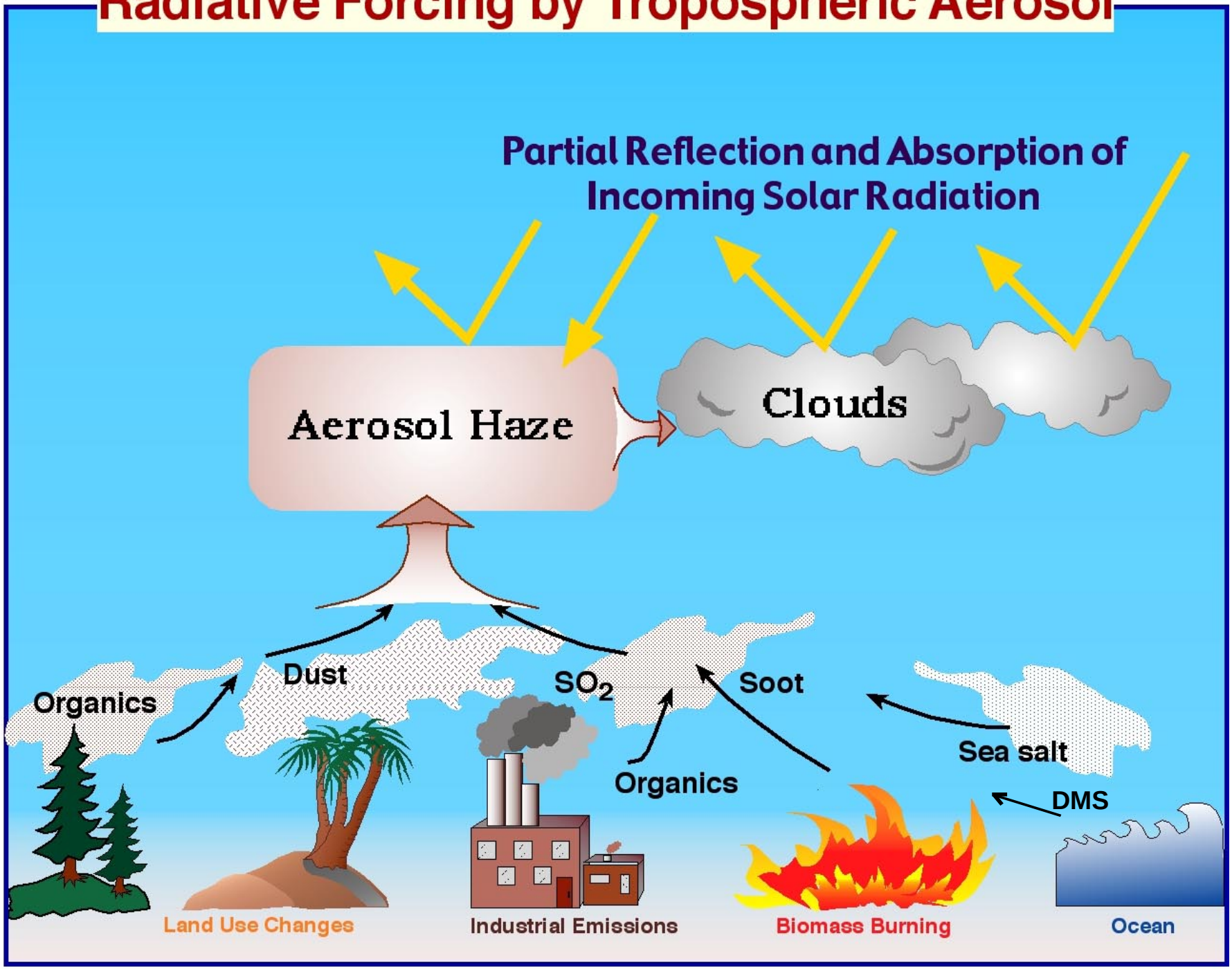
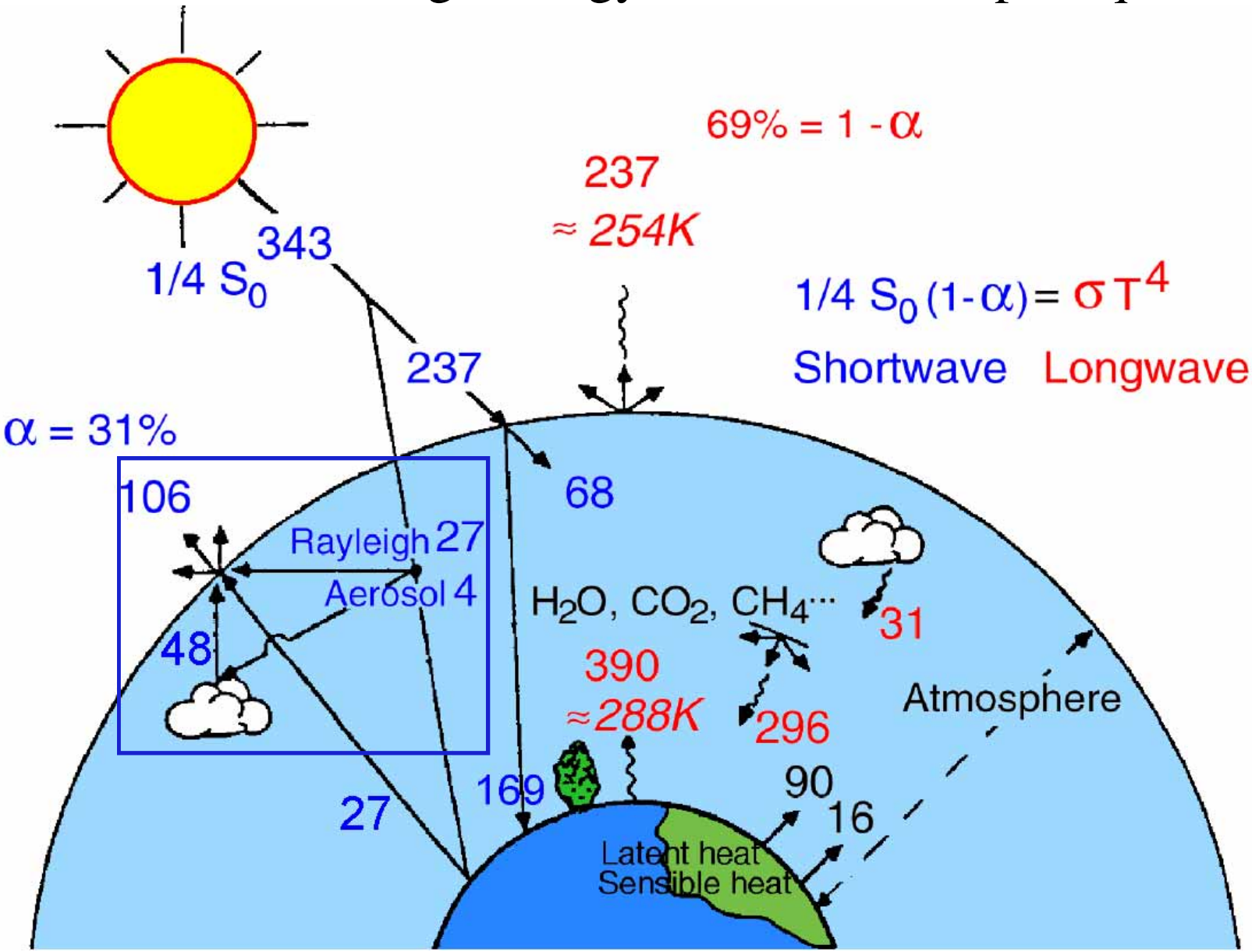
Radiative Forcing by Tropospheric Aerosol



GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

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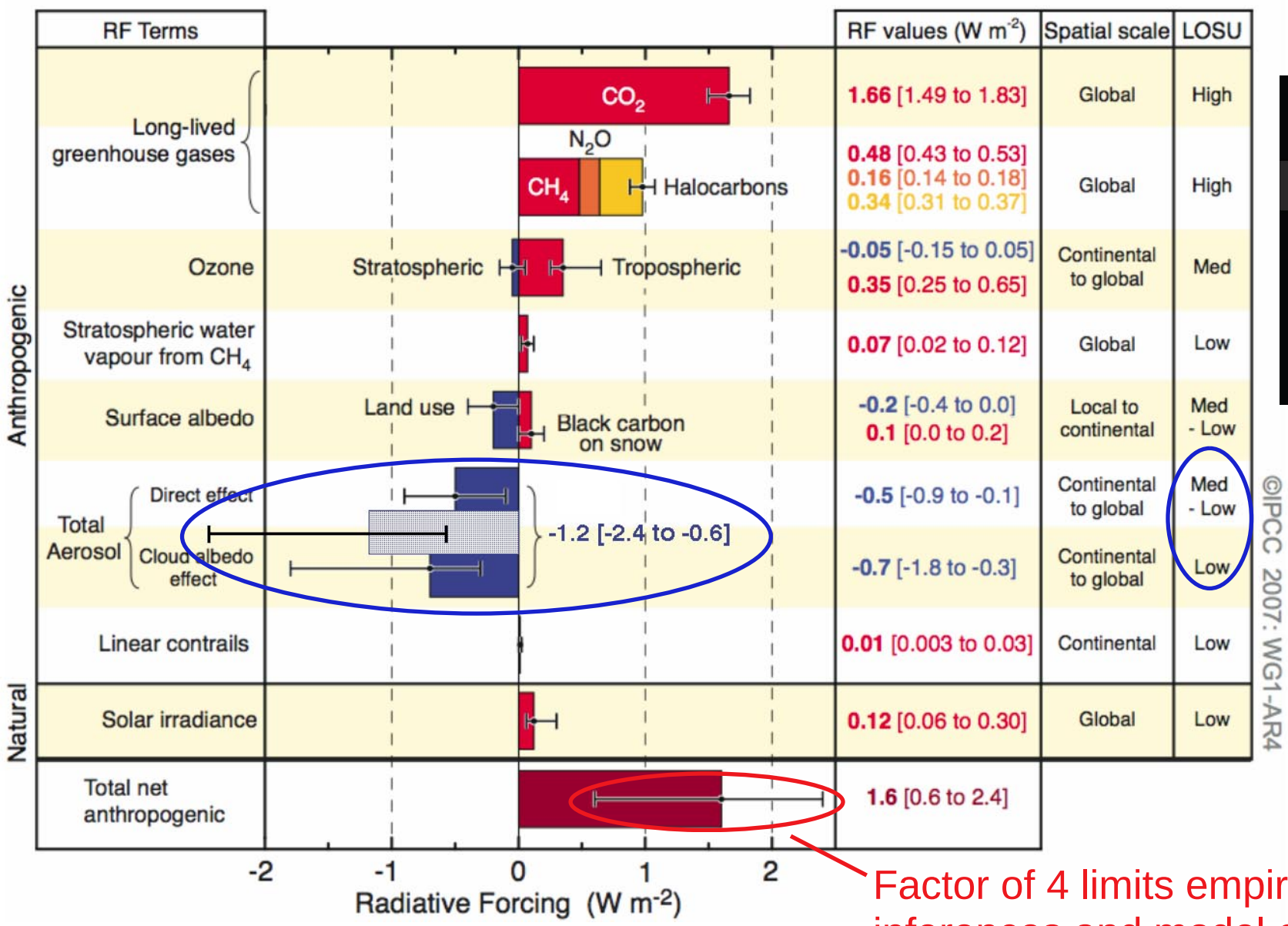
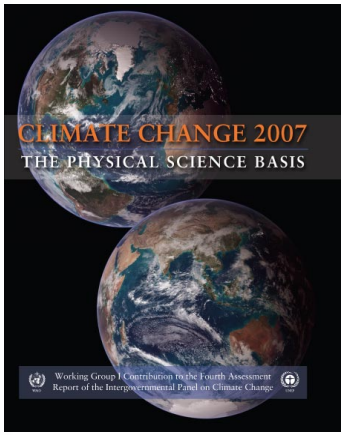


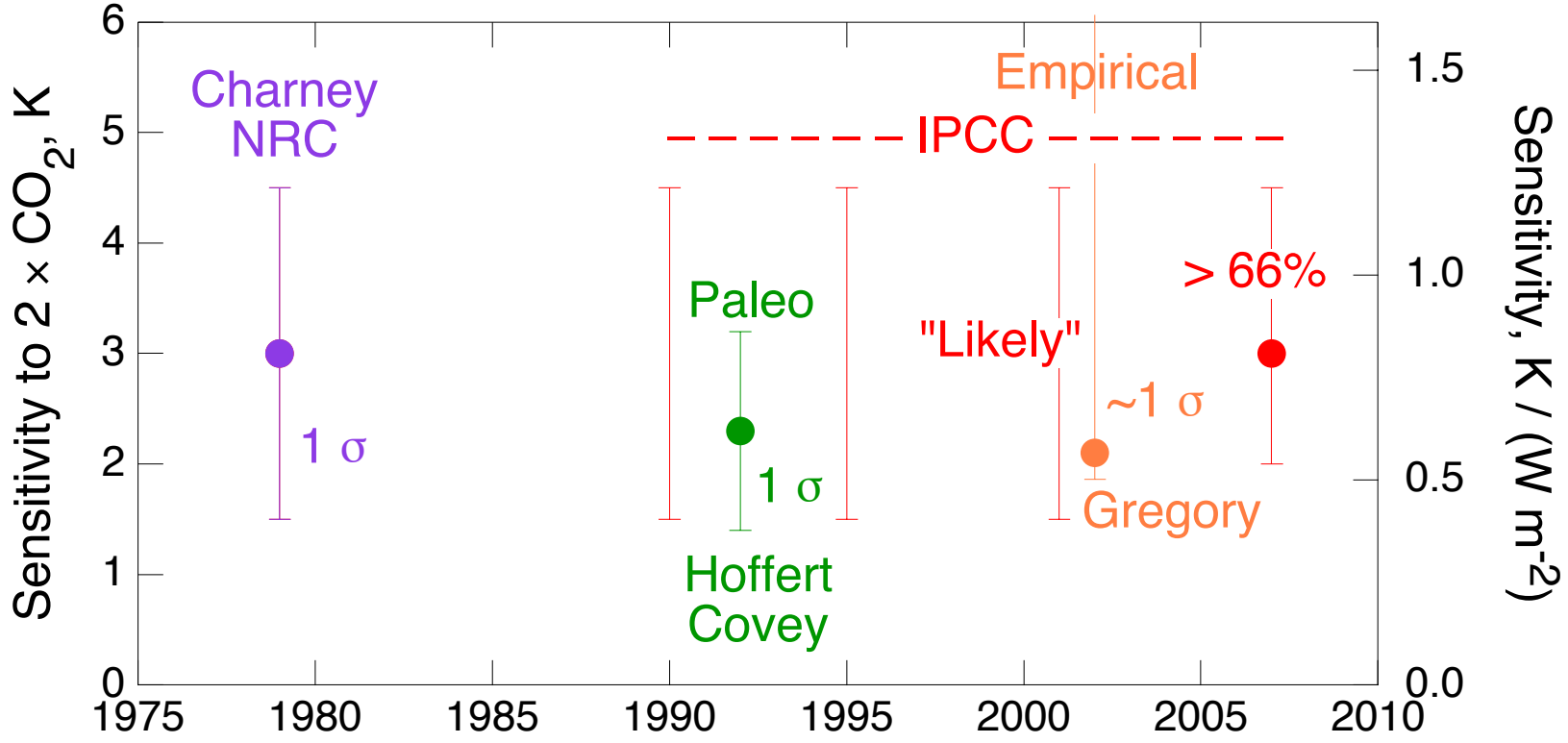


Factor of 4 limits empirical inferences and model evaluation.

LOSU denotes level of scientific understanding.

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

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



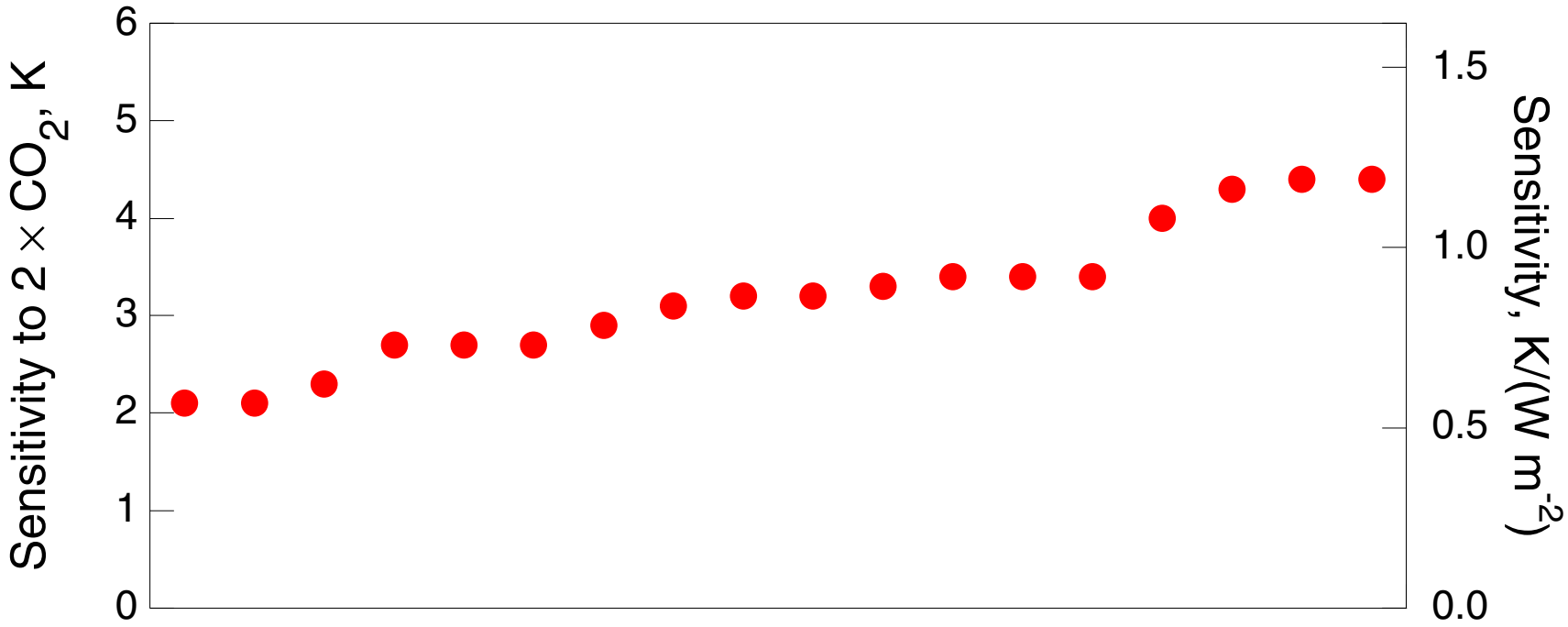
Empirical approach does not greatly constrain sensitivity because of uncertainty in aerosol forcing over the period of instrumental record.

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

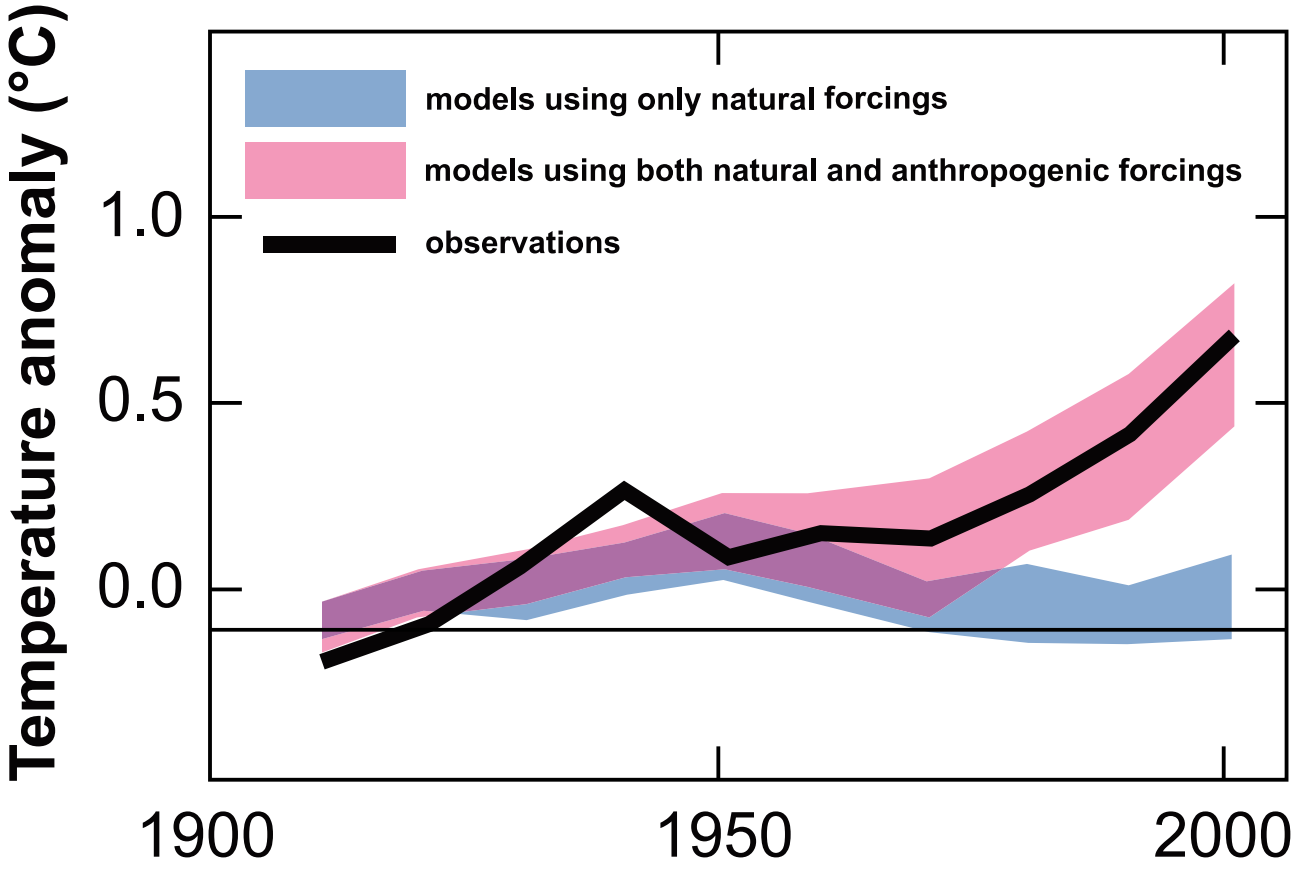
18 Current global climate models – IPCC AR4, 2007

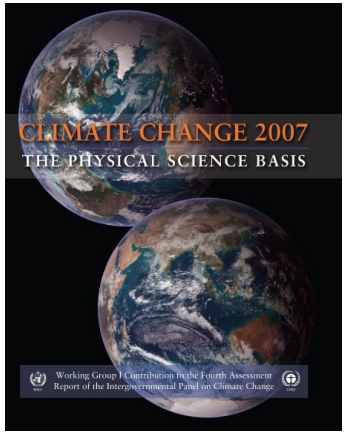


Range of model sensitivities is identical with range of current overall IPCC sensitivity estimate.

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models

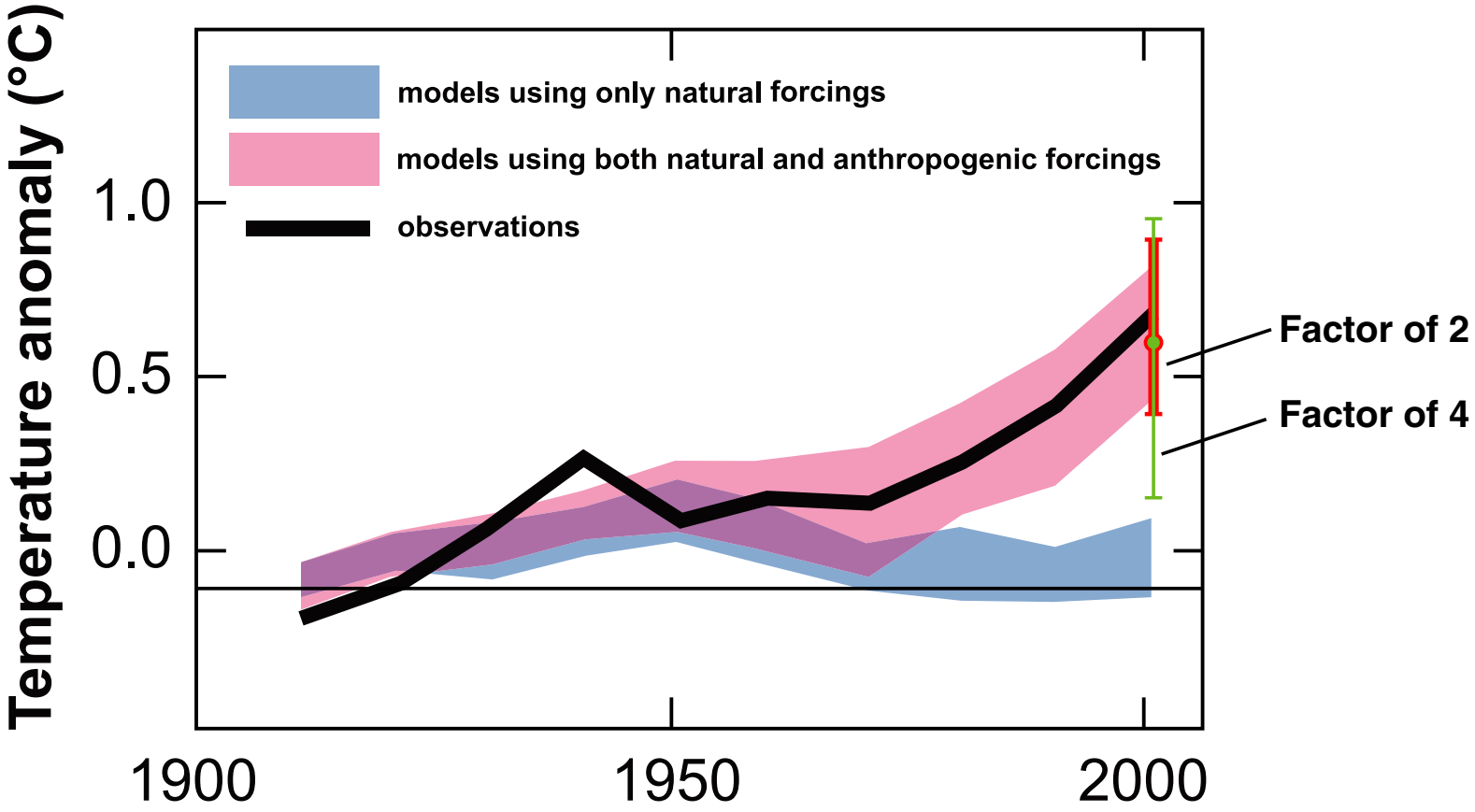




- Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a ***consistent explanation of the observed temperature record***.
- These simulations used models with ***different 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



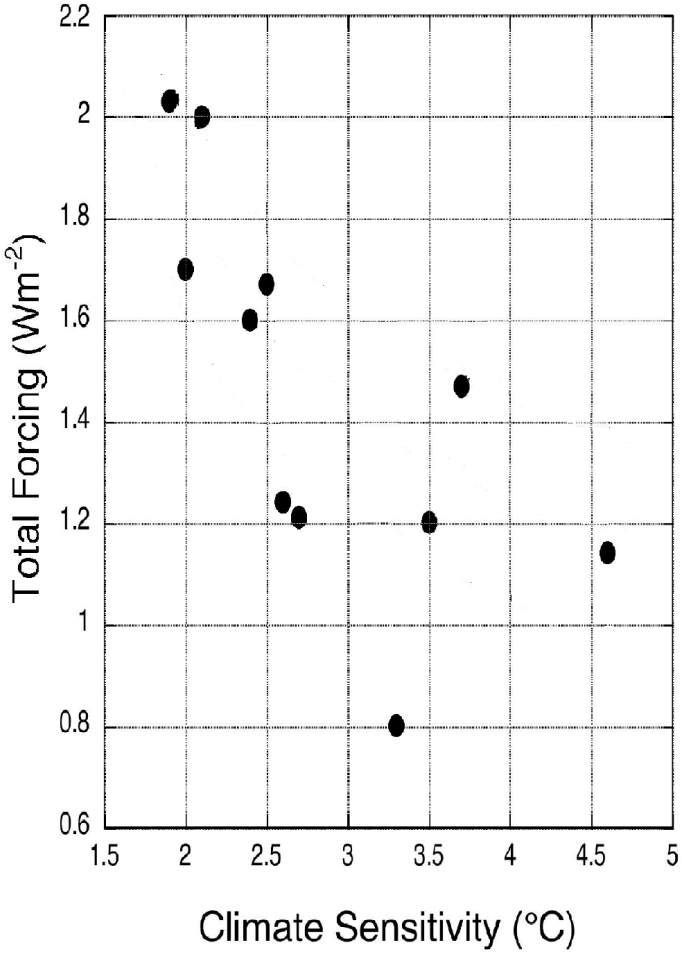
Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007

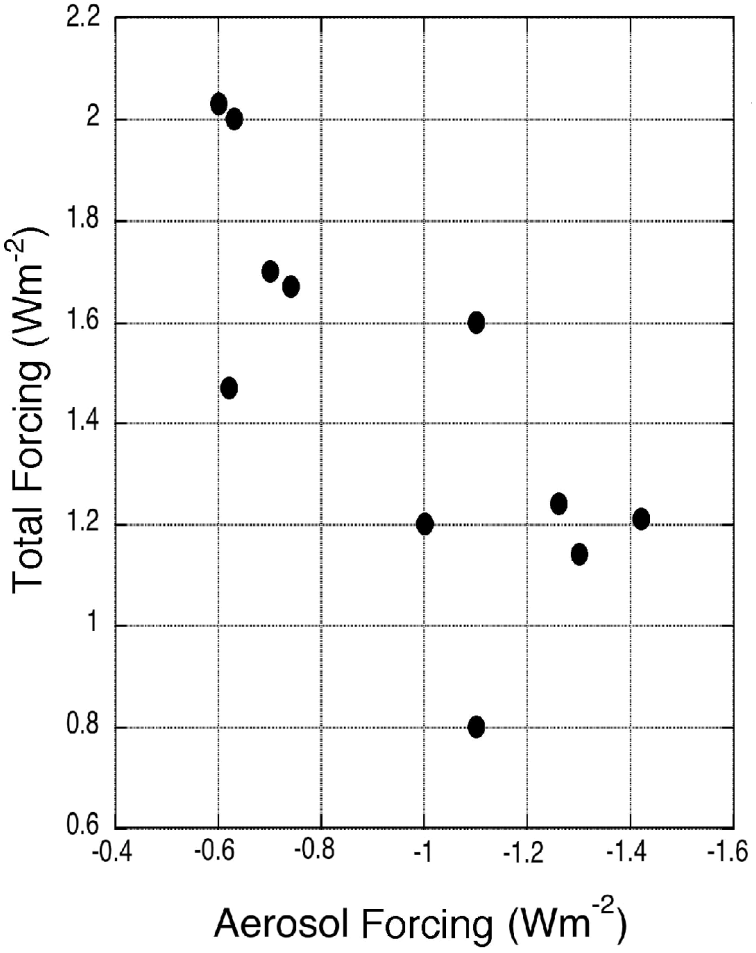
The models ***did not span the full range of the uncertainty*** and/or . . .

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

Climate models with higher sensitivity have lower total forcing.
Lower total forcing is due to greater (negative) aerosol forcing.

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- ***Climate modeling***: Understanding the processes that comprise Earth's climate system and representing them in large-scale numerical models.
- ***Energy-balance model***: Empirical determination from integral properties of Earth's climate system.

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

Global energy balance: $$C\frac{dT_S}{dt} = \boxed{\frac{dH}{dt} = Q - E} = \frac{\gamma J_S}{4} - \varepsilon\sigma T_S^4$$

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

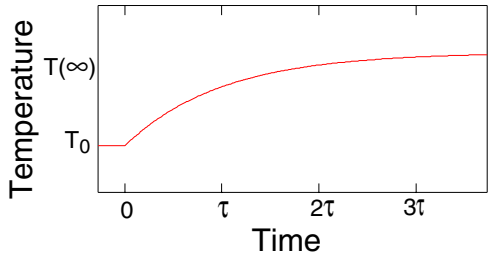
σ is Stefan-Boltzmann constant

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

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

If γ and ε are constant (***no feedbacks***), $S = \frac{T_0}{\gamma_0 J_S}$ Stefan-Boltzmann sensitivity, $S_{SB} = 0.30$ K/(W m^{-2}); $\Delta T_{2\times} = 1.1$ K

f is feedback *factor*

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

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

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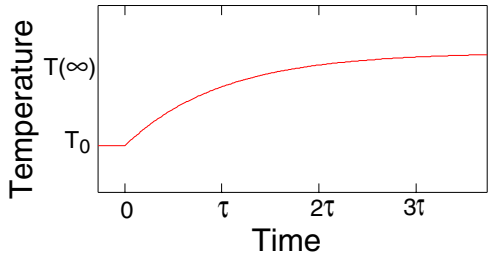
At "equilibrium" $\Delta T_S(\infty) = S\Delta F$



S is equilibrium climate sensitivity $\quad S = \dfrac{T_0}{\gamma_0 J_S} f = S_{SB} f$ $\quad$ 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 $\quad \tau = CS$ or $S = \tau / C$

One equation in three unknowns!

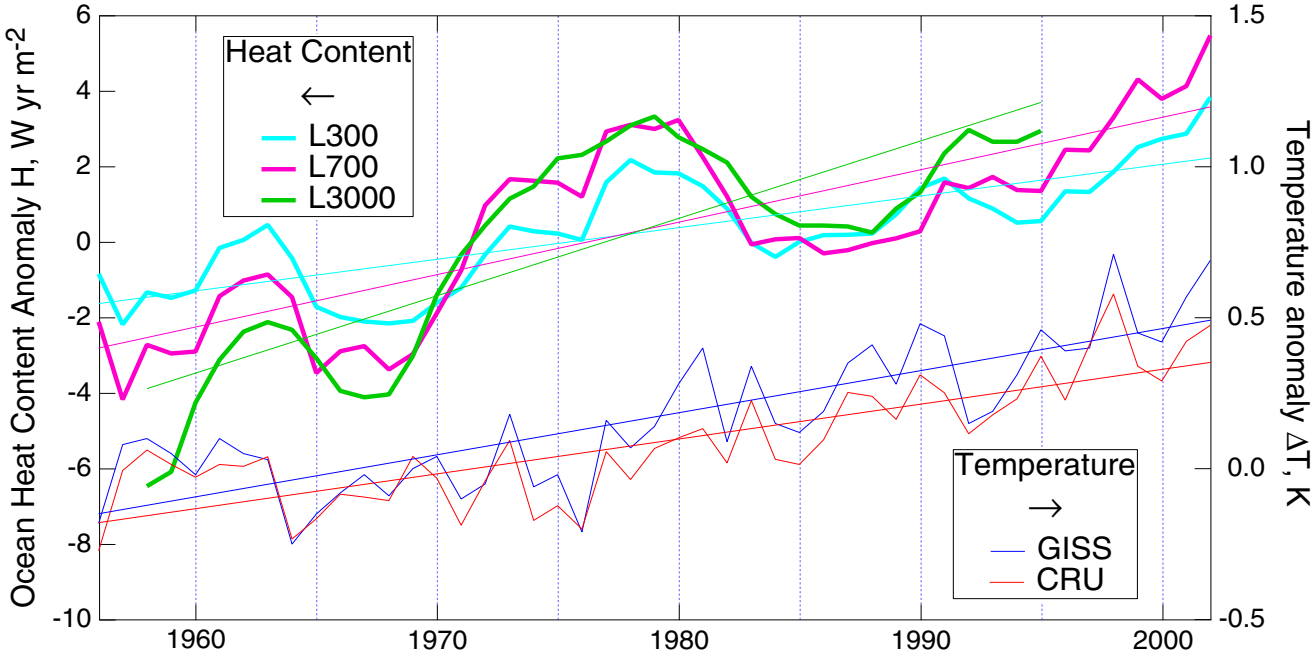
Approach: Determine C and τ from measurements; calculate sensitivity S.

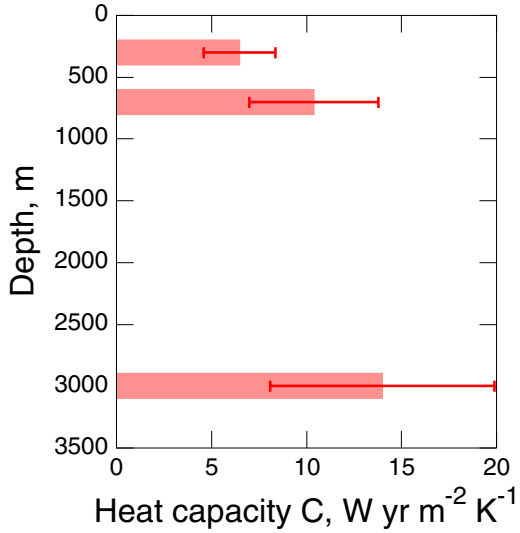
EMPIRICAL DETERMINATION OF OCEAN HEAT CAPACITY

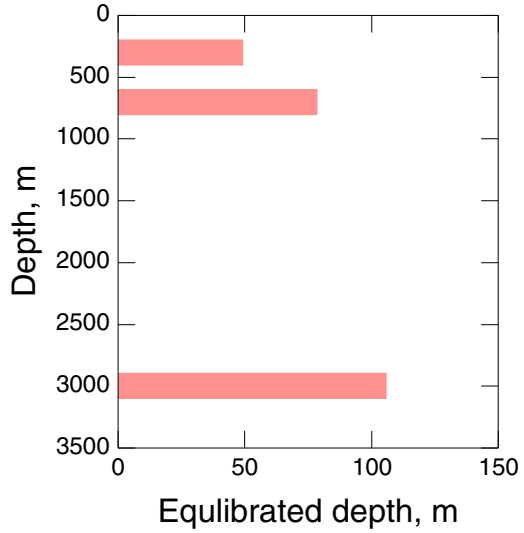
$$C = \frac{dH/dt}{dT_S/dt}$$

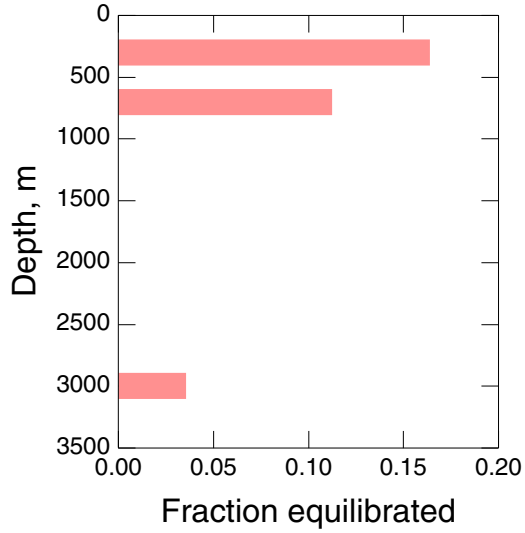
Ocean heat content H: Levitus *et al.*, GRL, 2005

Surface temperature T_S: GISS, CRU









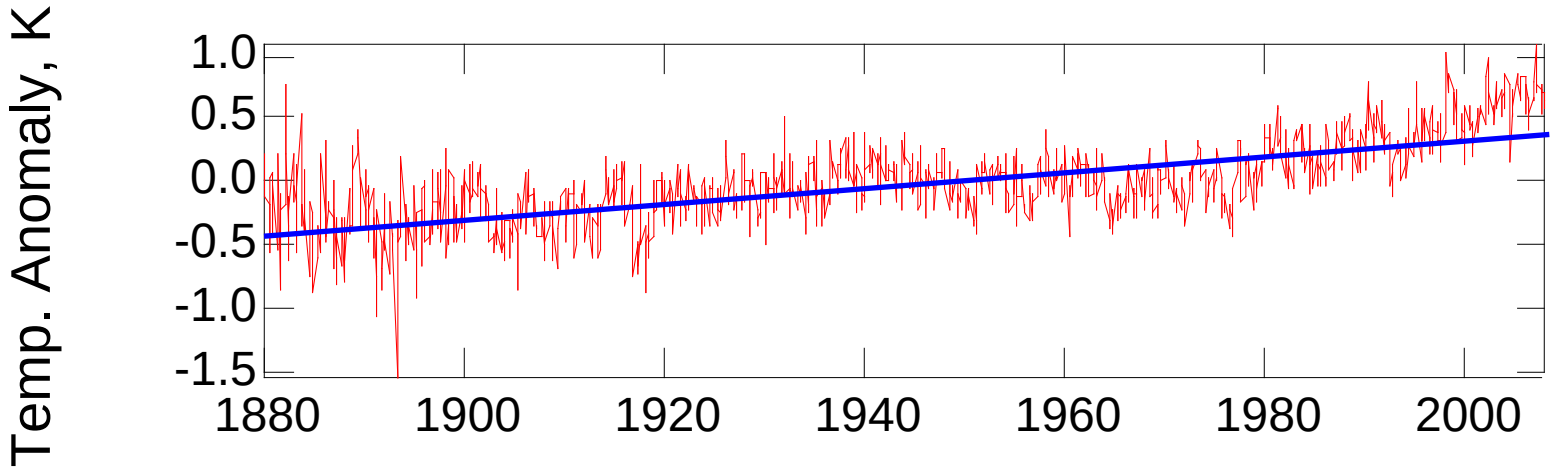
- ~50% of heat capacity is between surface and 300 m.
- Other heat sinks raise global heat capacity to 17 ± 7 W yr m^{-2} K^{-1}.

Schwartz, JGR, 2007

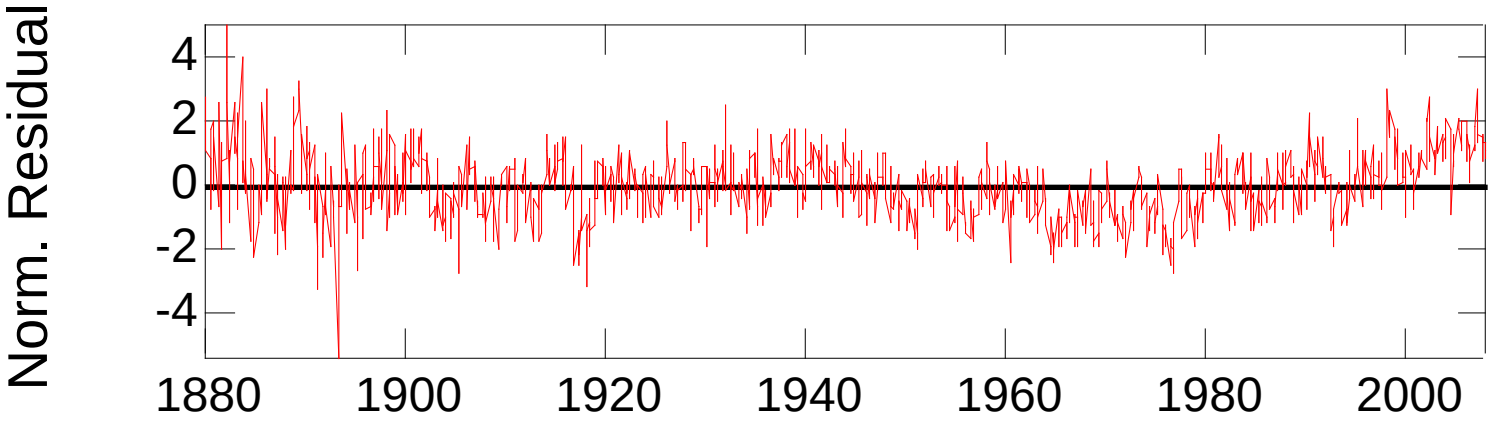
TIME CONSTANT OF EARTH'S CLIMATE SYSTEM

Determination from autocorrelation of time series

Input: Monthly global-mean surface temperature anomaly T_s



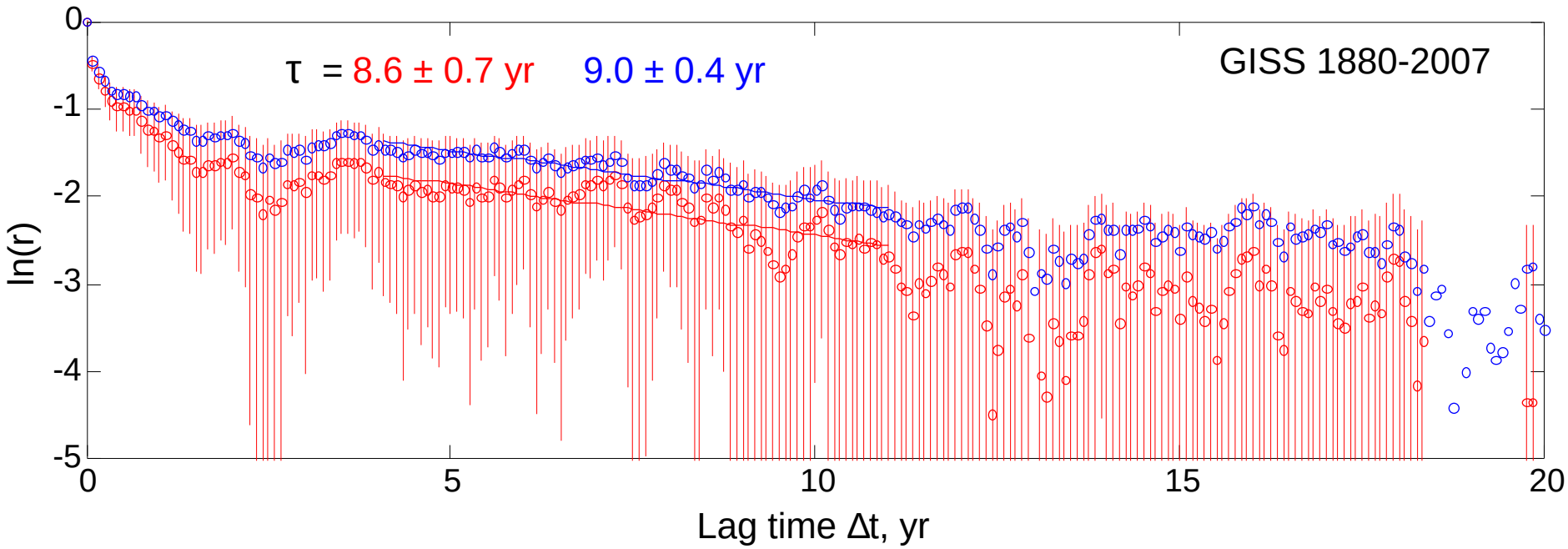
Remove long term trend; plot the residuals:



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

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**

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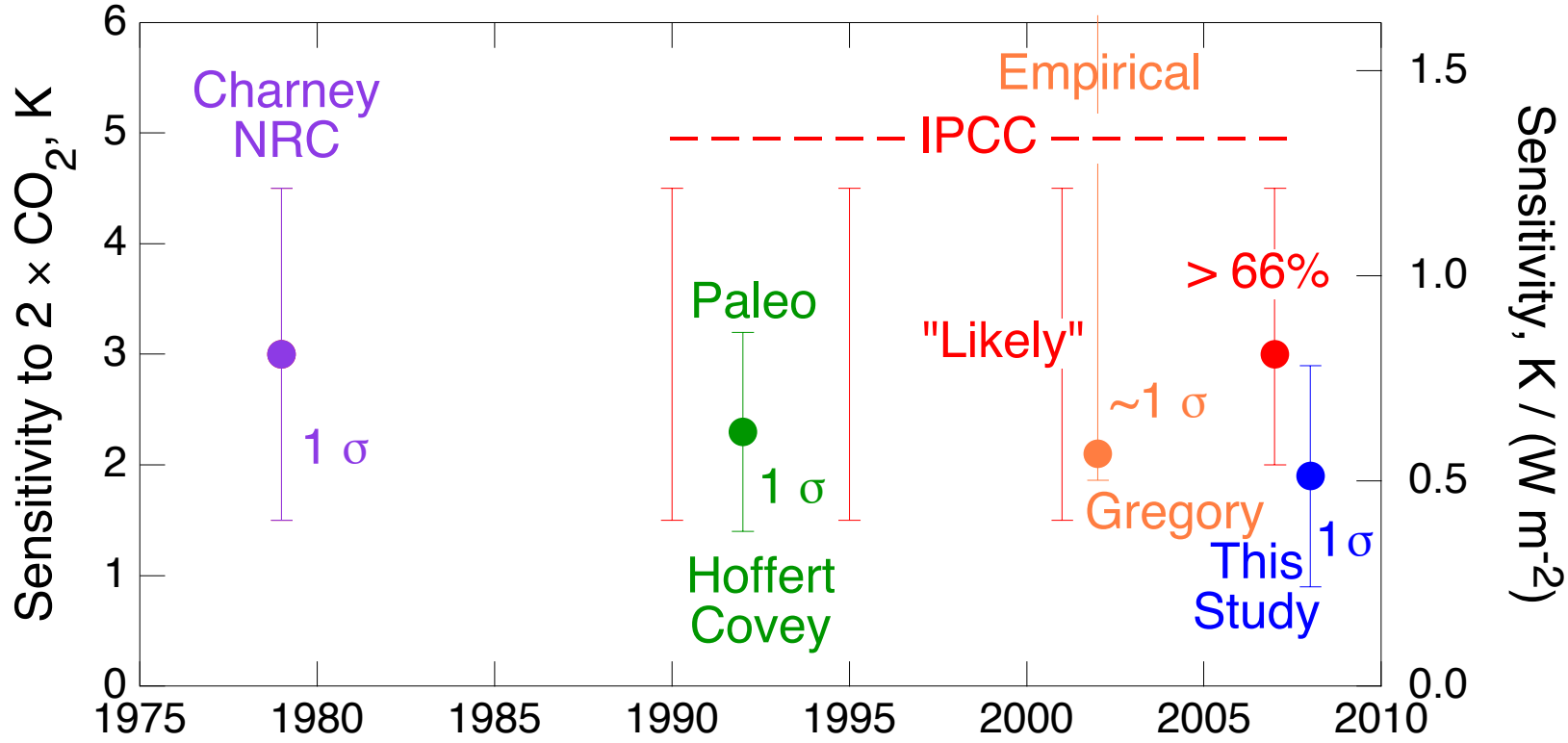
Estimates of central value and uncertainty range from specific approaches and major national and international assessments



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

EVALUATION OF SENSITIVITY AND FORCINGS

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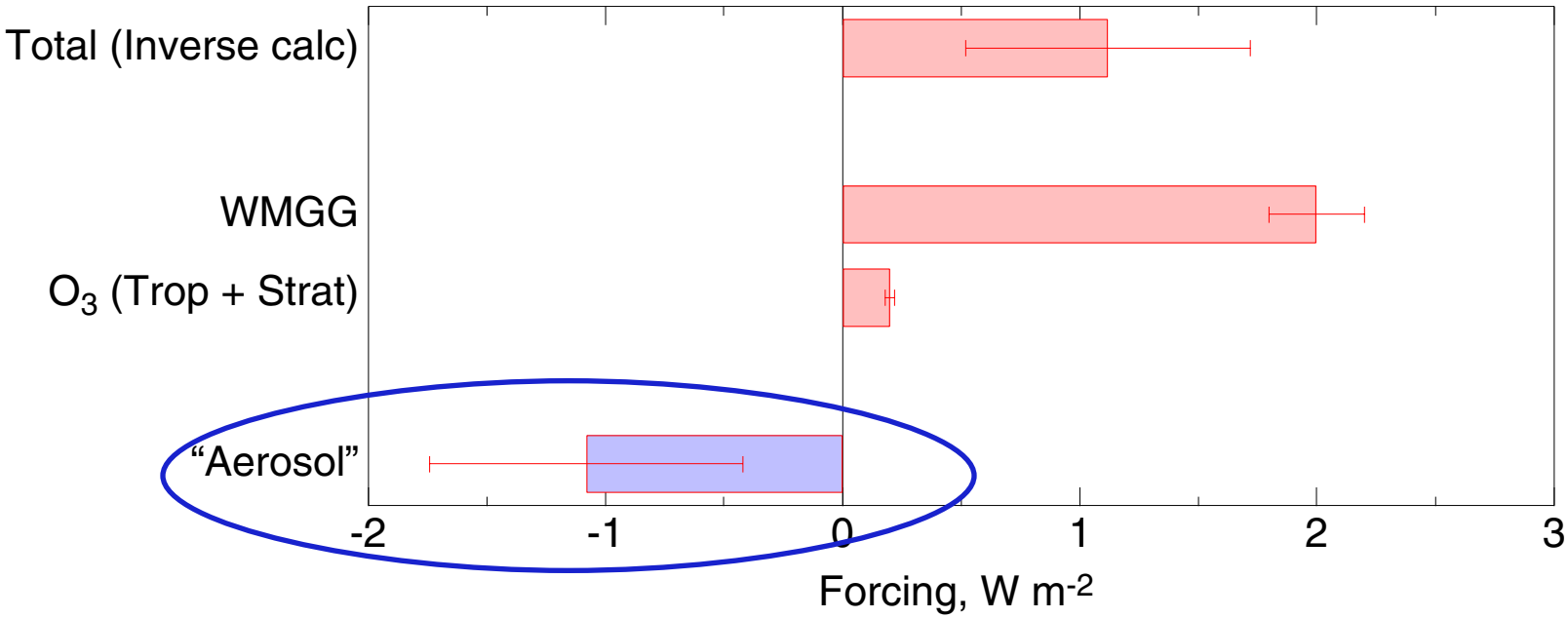
Feedback factor f	–	**1.7**	
Equilibrium temperature increase for $2 \times CO_2$, $\Delta T_{2\times}$	K	**1.9**	**1.0**
Total forcing over the 20th century, $F_{20} = \Delta T_{20} / S$ *Inverse calculation*	W m^{-2}	**1.1**	**0.6**
Forcing in 20th century other than GHGs (*mainly aerosols*), $F_{20}^{other} = F_{20} - F_{20}^{ghg}$	W m^{-2}	**-1.1**	**0.7**

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.