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

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Frontiers in Geoscience Colloquium

Los Alamos NATIONAL LABORATORY EST. 1943

February 12, 2007

Viewgraphs available on request from *ses@bnl.gov*

OUTLINE

Earth's energy balance, perturbations, and key questions
- Temperature change
- Sensitivity
- Forcing
- Response time

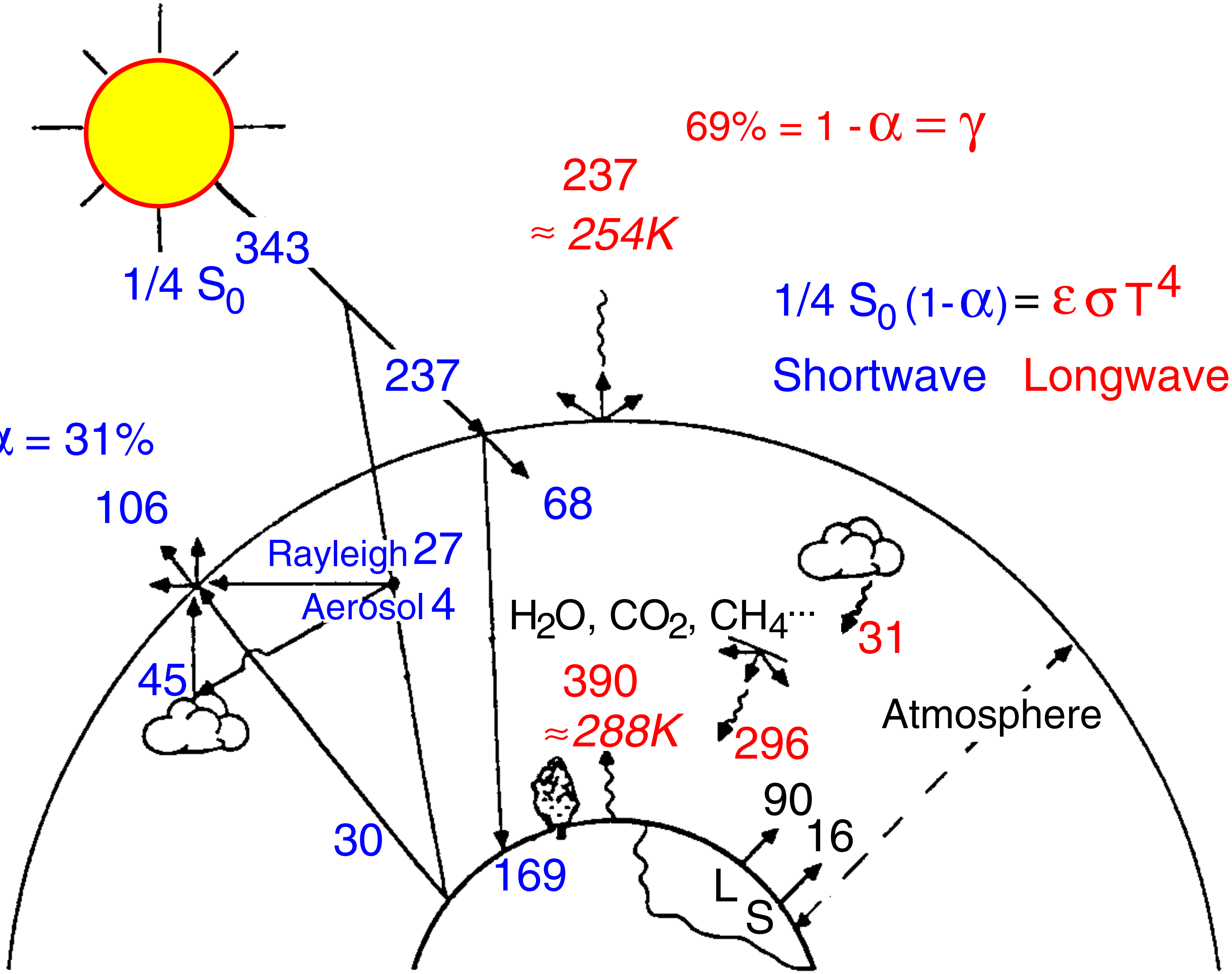
Energy balance models
- Stove-top model
- Billiard ball model
- Earth's climate system

Empirical determination of heat capacity, characteristic time, and sensitivity of Earth's climate system

Concluding observations

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



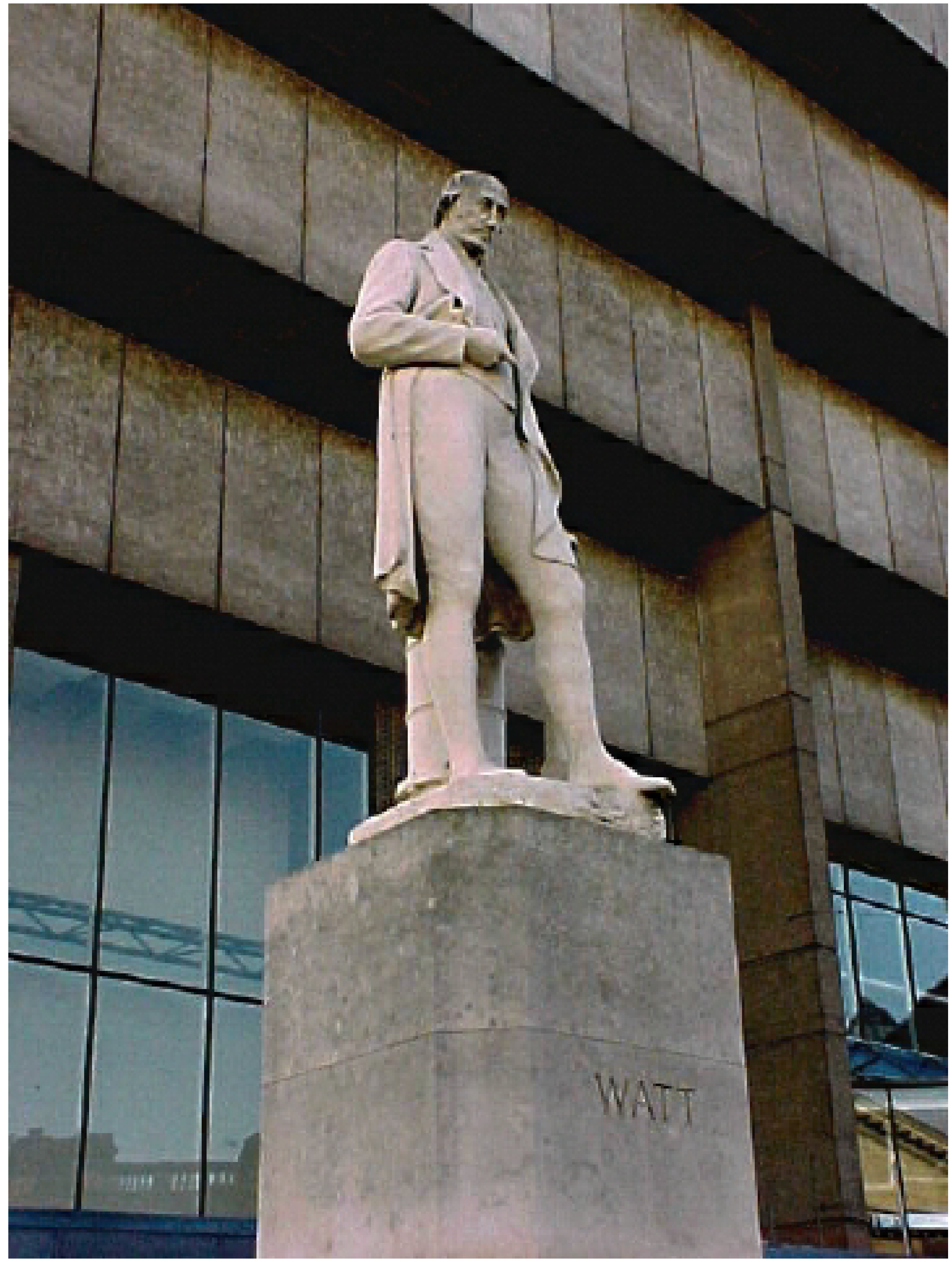
Schwartz, 1996, modified from Ramanathan, 1987

ATMOSPHERIC RADIATION

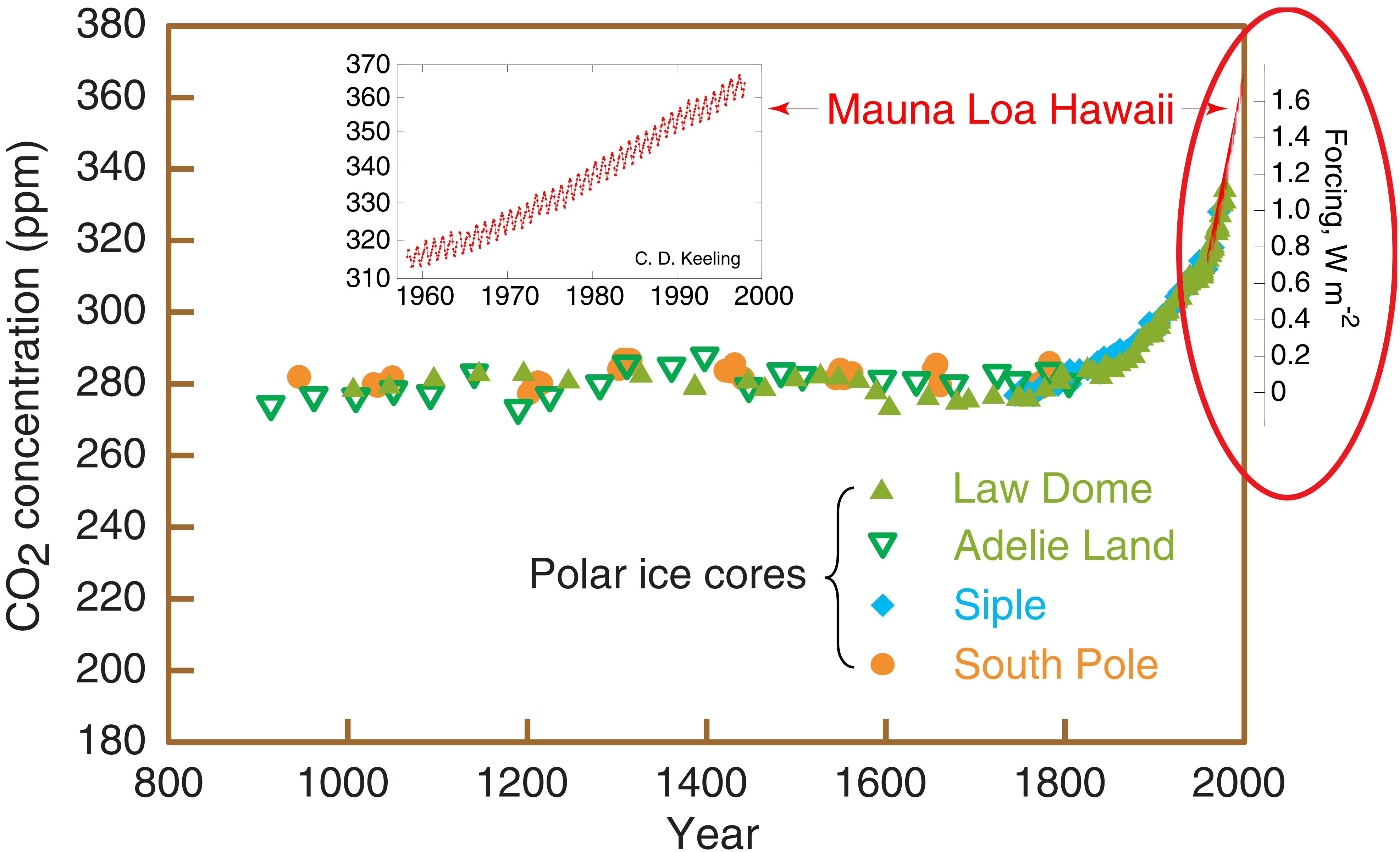
Energy per area per time

Power per area

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



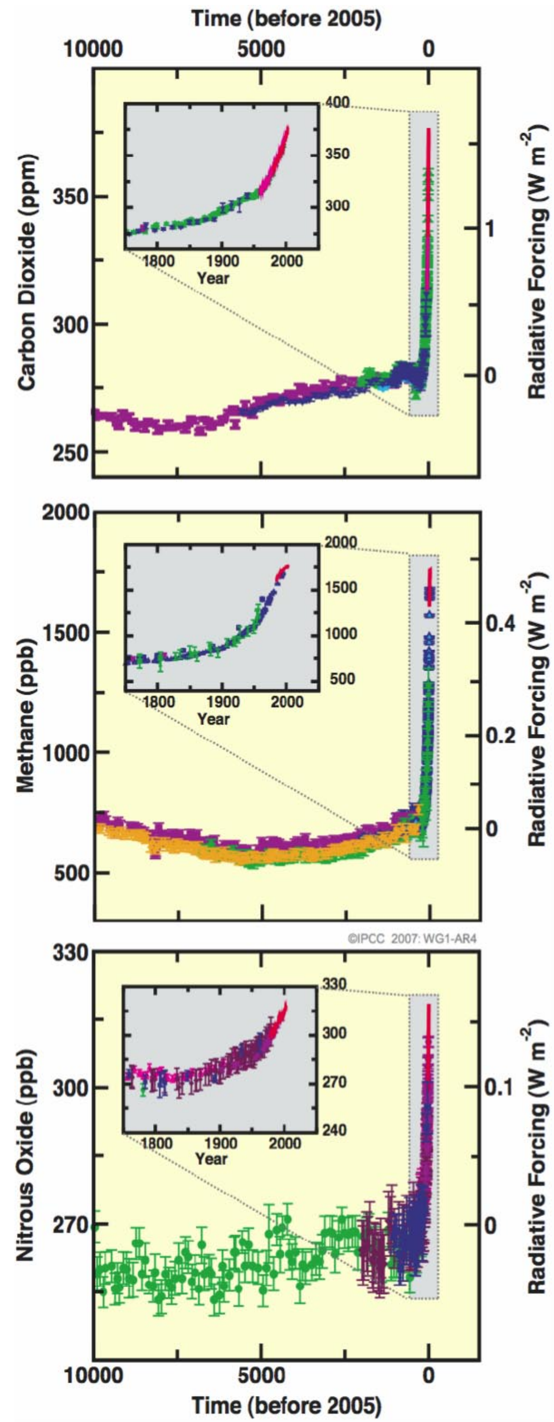
ATMOSPHERIC CARBON DIOXIDE IS INCREASING



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

ATMOSPHERIC GREENHOUSE GAS CONCENTRATIONS AND FORCINGS OVER THE LAST 10,000 YEARS

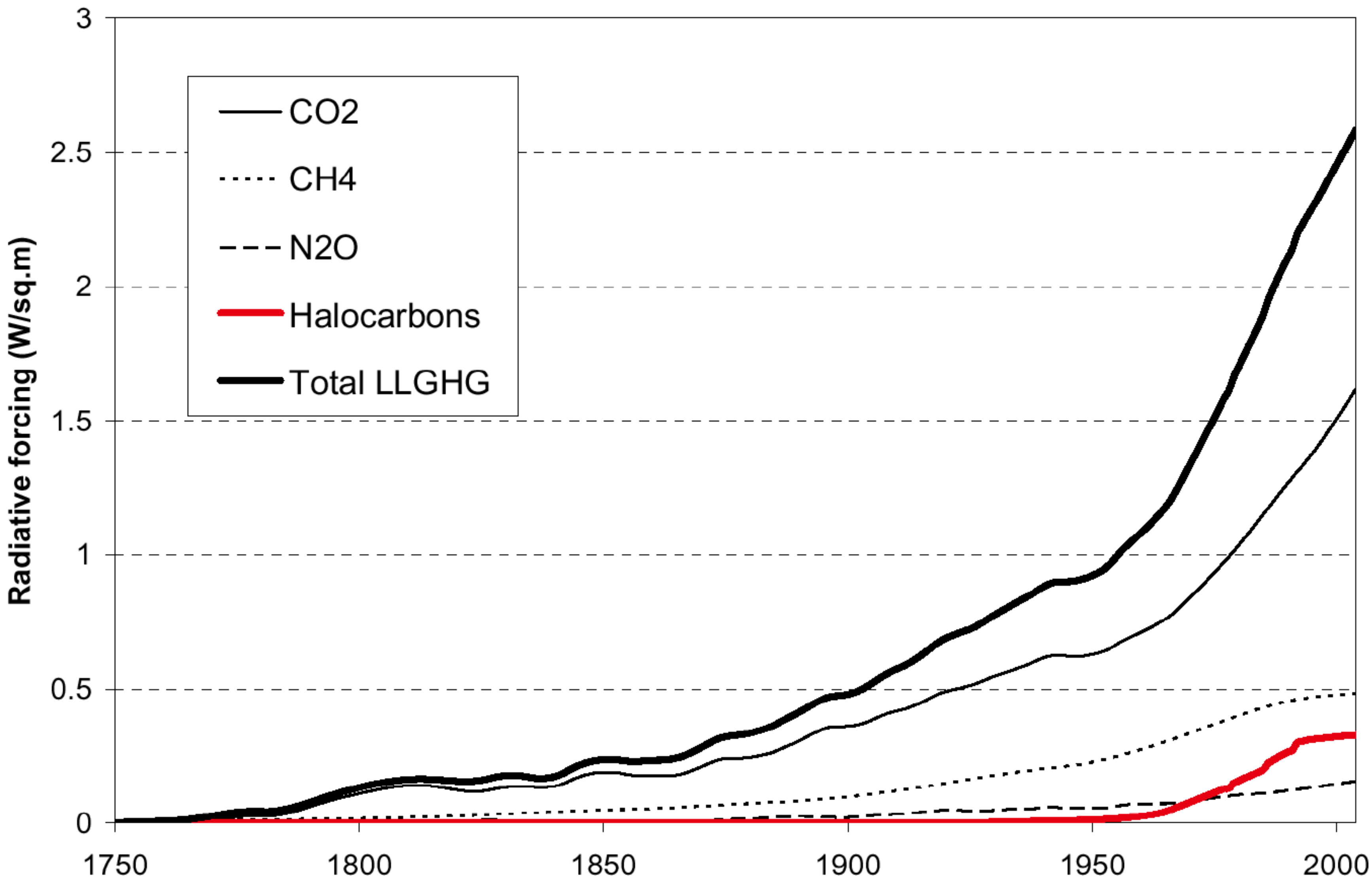
(Insets: 1750 – 2000)



IPCC, 2007

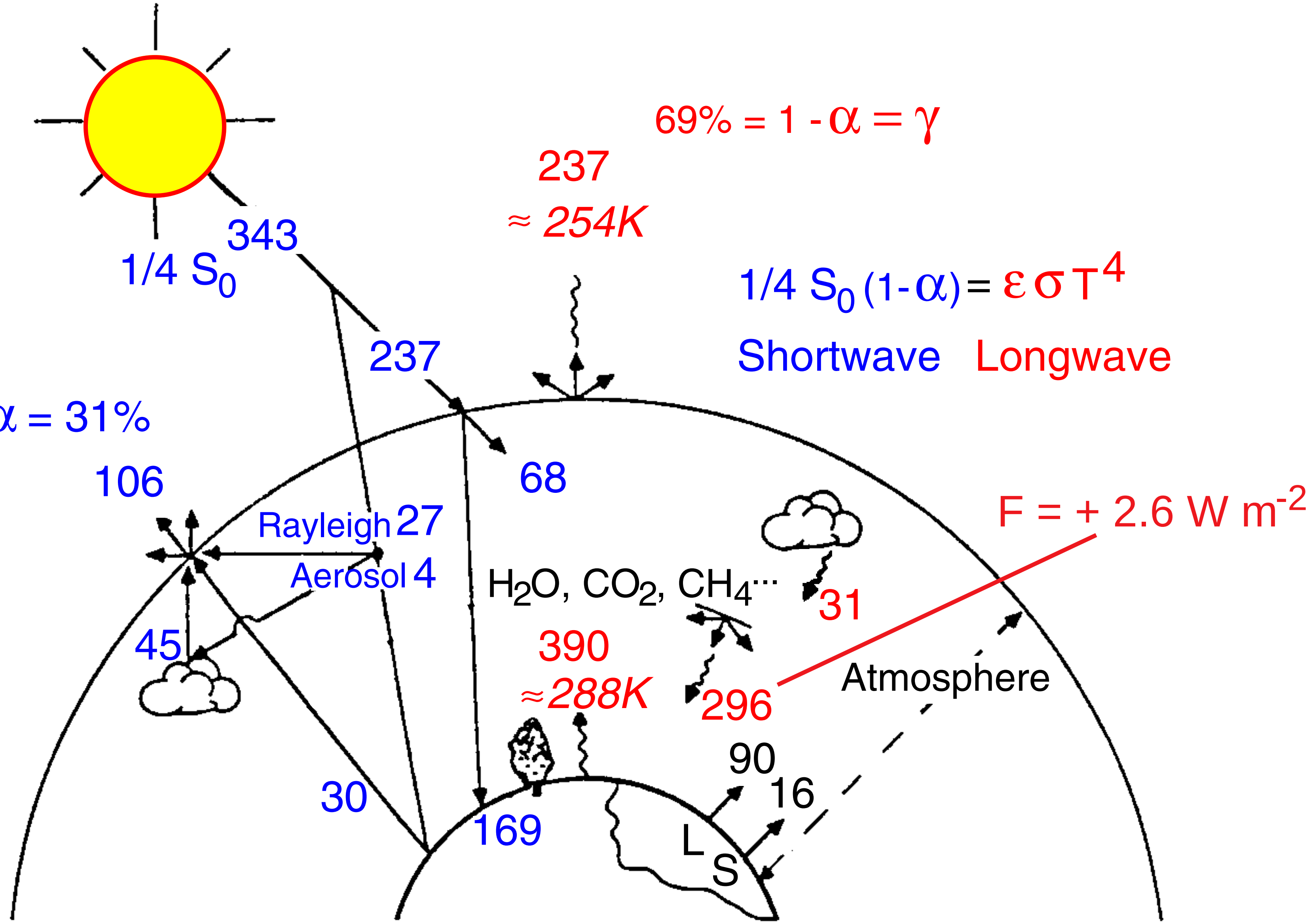
RADIATIVE FORCING BY LONG-LIVED GREENHOUSE GASES

Pre-industrial to present (IPCC, 2007)



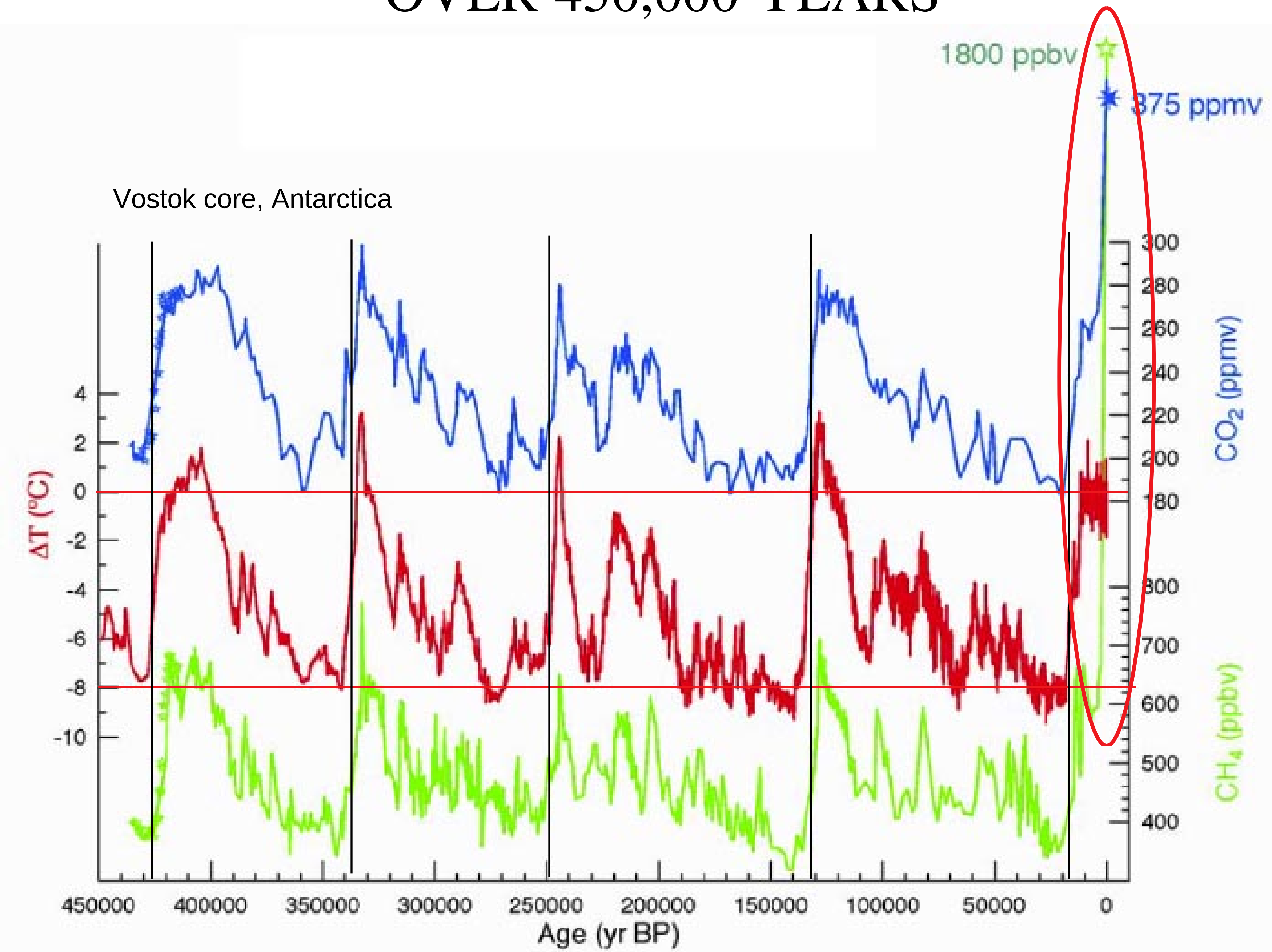
GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

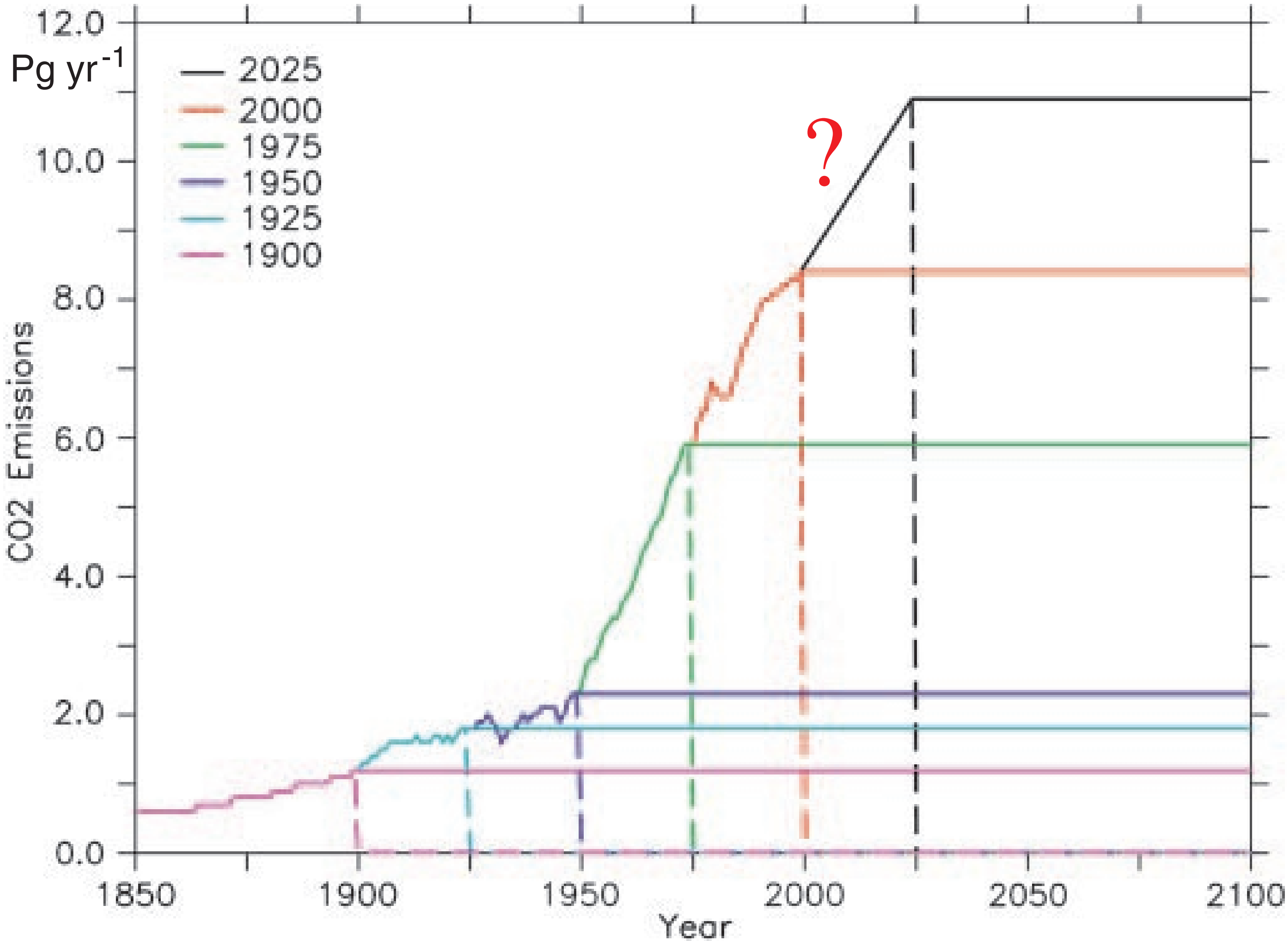
GREENHOUSE GASES AND TEMPERATURE OVER 450,000 YEARS



Modified from Petit et al., Nature, 1999

CARBON DIOXIDE ANNUAL EMISSIONS

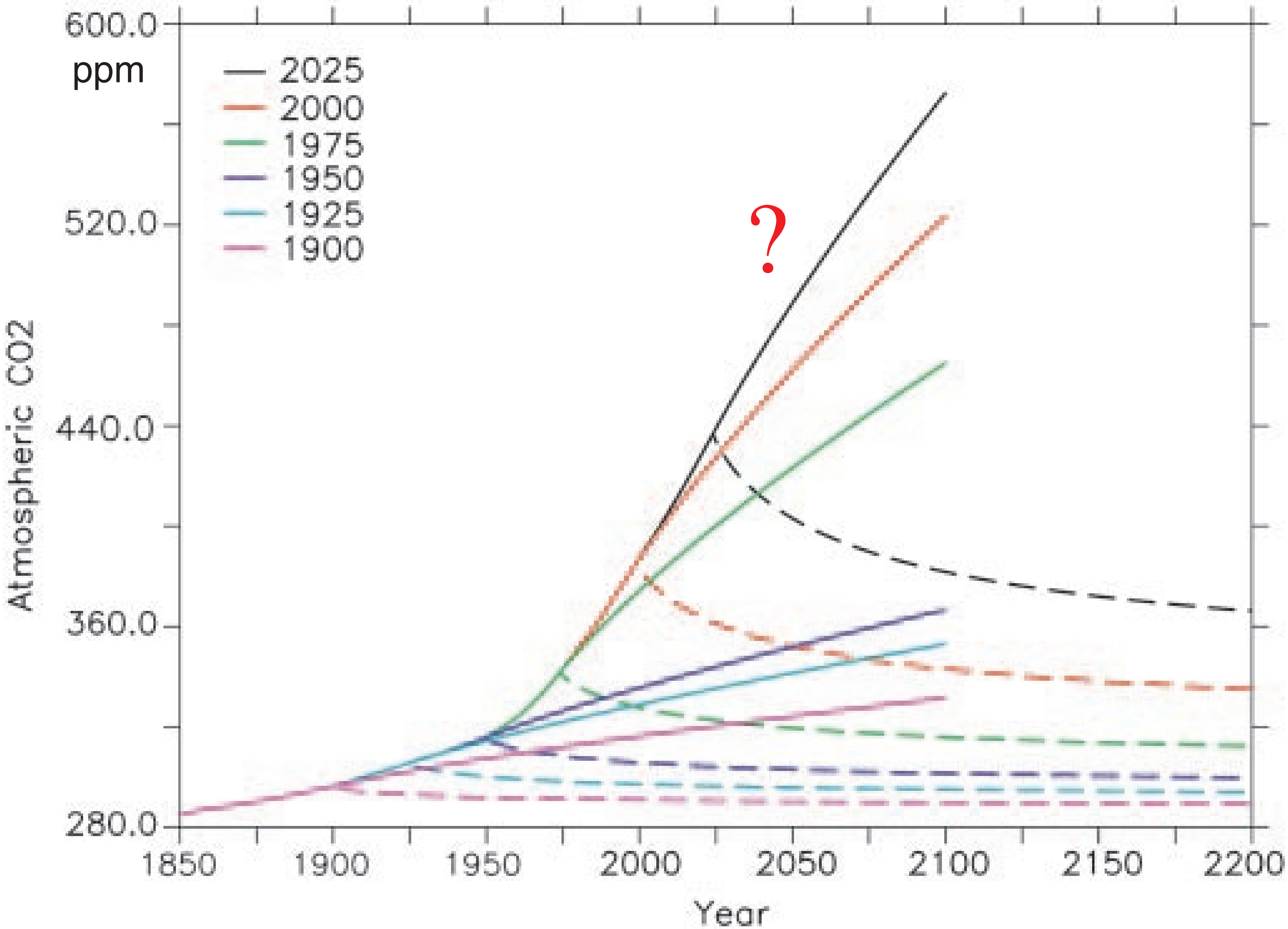
Past and Future



Friedlingstein and Solomon, PNAS, 2005

CARBON DIOXIDE IN THE ATMOSPHERE

Past and Future



Friedlingstein and Solomon, PNAS, 2005

AN ALTERNATIVE APPROACH

Remove carbon dioxide from the atmosphere

Richard Branson offers $25 million prize for method to remove CO_2 from the atmosphere.

FIRST ORDER QUESTIONS

How ***much*** will Earth's temperature change?

$$\Delta T_{\mathrm{eq}} = \lambda^{-1} F$$

What is the equilibrium sensitivity λ^{-1} ?

What is the forcing F ?

How ***fast*** will Earth's temperature change?

What is the $1/e$ time constant characterizing climate change τ ?

WHY IS THIS IMPORTANT?

Prevent “dangerous anthropogenic interference” with the climate system.

“My precautionary evaluation of current understanding of the ice sheets would support 2˚C warming above the current global mean temperature as a long-term target.

– *M. Oppenheimer, 2005*

“Based on the paleoclimate evidence, I suggest that the highest prudent level of additional global warming is not more than about 1˚C.

– *J. Hansen, 2004*

UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE (1992)

“ The ultimate objective of this Convention ... is to achieve ... ***stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system***.

“ The Parties should take precautionary measures to ***anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects***.

“ Where there are threats of serious or irreversible damage, ***lack of full scientific certainty should not be used as a reason for postponing such measures***.

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* By Prof. SVANTE ARRHENIUS *.

TABLE VII.—*Variation of Temperature caused by a given Variation of Carbonic Acid.*

Latitude.	Carbonic Acid=0·67.					Carbonic Acid=1·5.				
	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70–60	−2·9	−3·0	−3·4	−3·1	−3·1	3·3	3·4	3·8	3·6	3·52
60–50	−3·0	−3·2	−3·4	−3·3	−3·22	3·4	3·7	3·6	3·8	3·62
50–40	−3·2	−3·3	−3·3	−3·4	−3·3	3·7	3·8	3·4	3·7	3·65
40–30	−3·4	−3·4	−3·2	−3·3	−3·32	3·7	3·6	3·3	3·5	3·52
30–20	−3·3	−3·2	−3·1	−3·1	−3·17	3·5	3·3	3·2	3·5	3·47
20–10	−3·1	−3·1	−3·0	−3·1	−3·07	3·5	3·2	3·1	3·2	3·25
10–0	−3·1	−3·0	−3·0	−3·0	−3·02	3·2	3·2	3·1	3·1	3·15
0–−10	−3·0	−3·0	−3·1	−3·0	−3·02	3·1	3·1	3·2	3·2	3·15
−10–−20	−3·1	−3·1	−3·2	−3·1	−3·12	3·2	3·2	3·2	3·2	3·2
−20–−30	−3·1	−3·2	−3·3	−3·2	−3·2	3·2	3·2	3·4	3·3	3·27
−30–−40	−3·3	−3·3	−3·4	−3·4	−3·35	3·4	3·5	3·7	3·5	3·52
−40–−50	−3·4	−3·4	−3·3	−3·4	−3·37	3·6	3·7	3·8	3·7	3·7
−50–−60	−3·2	−3·3	—	—	—	3·8	3·7	—	—	—

Latitude.	Carbonic Acid=2·0.					Carbonic Acid=2·5.					Carbonic Acid=3·0.				
	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70–60	6·0	6·1	6·0	6·1	6·05	7·9	8·0	7·9	8·0	7·95	9·1	9·3	9·4	9·4	9·3
60–50	6·1	6·1	5·8	6·1	6·02	8·0	8·0	7·6	7·9	7·87	9·3	9·5	8·9	9·5	9·3
50–40	6·1	6·1	5·5	6·0	5·92	8·0	7·9	7·0	7·9	7·7	9·5	9·4	8·6	9·2	9·17
40–30	6·0	5·8	5·4	5·6	5·7	7·9	7·6	6·9	7·3	7·42	9·3	9·0	8·2	8·8	8·82
30–20	5·6	5·4	5·0	5·2	5·3	7·2	7·0	6·6	6·7	6·87	8·7	8·3	7·5	7·9	8·1
20–10	5·2	5·0	4·9	5·0	5·02	6·7	6·6	6·3	6·6	6·52	7·9	7·5	7·2	7·5	7·52
10–0	5·0	5·0	4·9	4·9	4·95	6·6	6·4	6·3	6·4	6·42	7·4	7·3	7·2	7·3	7·3
0–−10	4·9	4·9	5·0	5·0	4·95	6·4	6·4	6·6	6·6	6·5	7·3	7·3	7·4	7·4	7·35
−10–−20	5·0	5·0	5·2	5·1	5·07	6·6	6·6	6·7	6·7	6·65	7·4	7·5	8·0	7·6	7·62
−20–−30	5·2	5·3	5·5	5·4	5·35	6·7	6·8	7·0	7·0	6·87	7·9	8·1	8·6	8·3	8·22
−30–−40	5·5	5·6	5·8	5·6	5·62	7·0	7·2	7·7	7·4	7·32	8·6	8·7	9·1	8·8	8·8
−40–−50	5·8	6·0	6·0	6·0	5·95	7·7	7·9	7·9	7·9	7·85	9·1	9·2	9·4	9·3	9·25
−50–−60	6·0	6·1	—	—	—	7·9	8·0	—	—	—	9·4	9·5	—	—	—

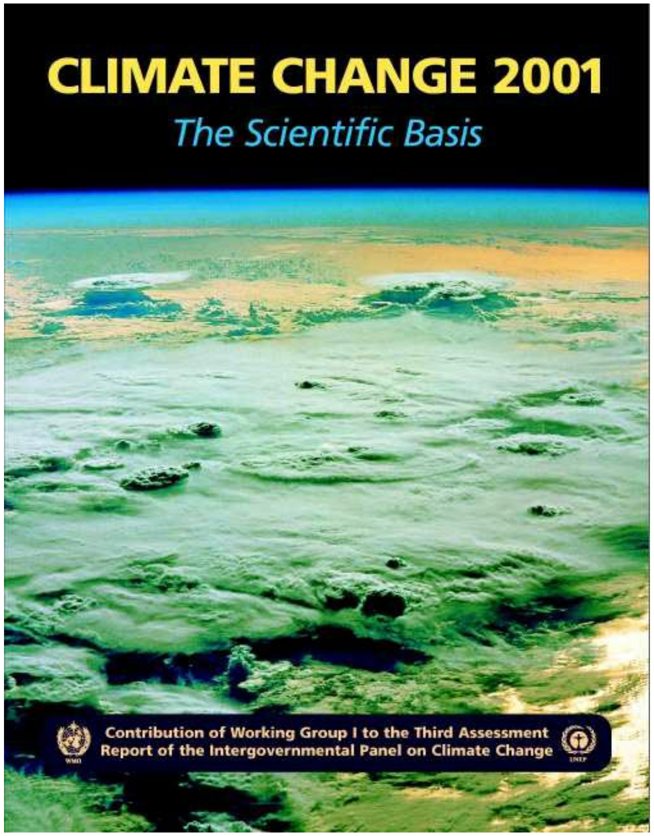
Global Average: 5.47

Ad Hoc Study Group on Carbon Dioxide and Climate

Report of an Ad Hoc Study Group on Carbon Dioxide and Climate
Woods Hole, Massachusetts
July 23–27, 1979
to the
Climate Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

Jule G. Charney, Massachusetts Institute of Technology, *Chairman*
Akio Arakawa, University of California, Los Angeles
D. James Baker, University of Washington
Bert Bolin, University of Stockholm
Robert E. Dickinson, National Center for Atmospheric Research
Richard M. Goody, Harvard University
Cecil E. Leith, National Center for Atmospheric Research
Henry M. Stommel, Woods Hole Oceanographic Institution
Carl I. Wunsch, Massachusetts Institute of Technology

of terrestrial radiation. We have examined with care all known negative feedback mechanisms, such as increase in low or middle cloud amount, and have concluded that the oversimplifications and inaccuracies in the models are not likely to have vitiated the principal conclusion that there will be appreciable warming. The known negative feedback mechanisms can reduce the warming, but they do not appear to be so strong as the positive moisture feedback. We estimate the most probable global warming for a doubling of CO_2 to be near 3°C with a probable error of ± 1.5°C. Our estimate is based primarily on our review of a series of calculations with three-dimensional models of the global atmospheric circulation, which is summarized in Chapter 4. We have also reviewed simpler models that appear to contain the main physical factors. These give qualitatively similar results.



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Climate Scientist, Technical Support Unit, Working Group I, IPCC

F.3 Projections of Future Changes in Temperature

AOGCM results

Climate sensitivity is likely to be in the range of 1.5 to 4.5°C. This estimate is unchanged from the first IPCC Assessment Report in 1990 and the SAR. The climate sensitivity is the equilibrium response of global surface temperature to a doubling of equivalent CO_2 concentration. The range of estimates arises from uncertainties in the climate models and their internal feedbacks, particularly those related to clouds and related

WMO

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

UNEP

Climate Change 2007: The Physical Science Basis

Summary for Policymakers

Contribution of Working Group I to the Fourth Assessment Report

This Summary for Policymakers was formally approved at the 10th Session of Working Group I of the IPCC, Paris, February 2007.

The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is not a projection but is defined as the global average surface warming following a doubling of carbon dioxide concentrations. It is *likely* to be in the range 2 to 4.5°C with a best estimate of about 3°C, and is *very unlikely* to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values. Water vapour changes represent the largest feedback affecting climate sensitivity and are now better understood than in the TAR. Cloud feedbacks remain the largest source of uncertainty.

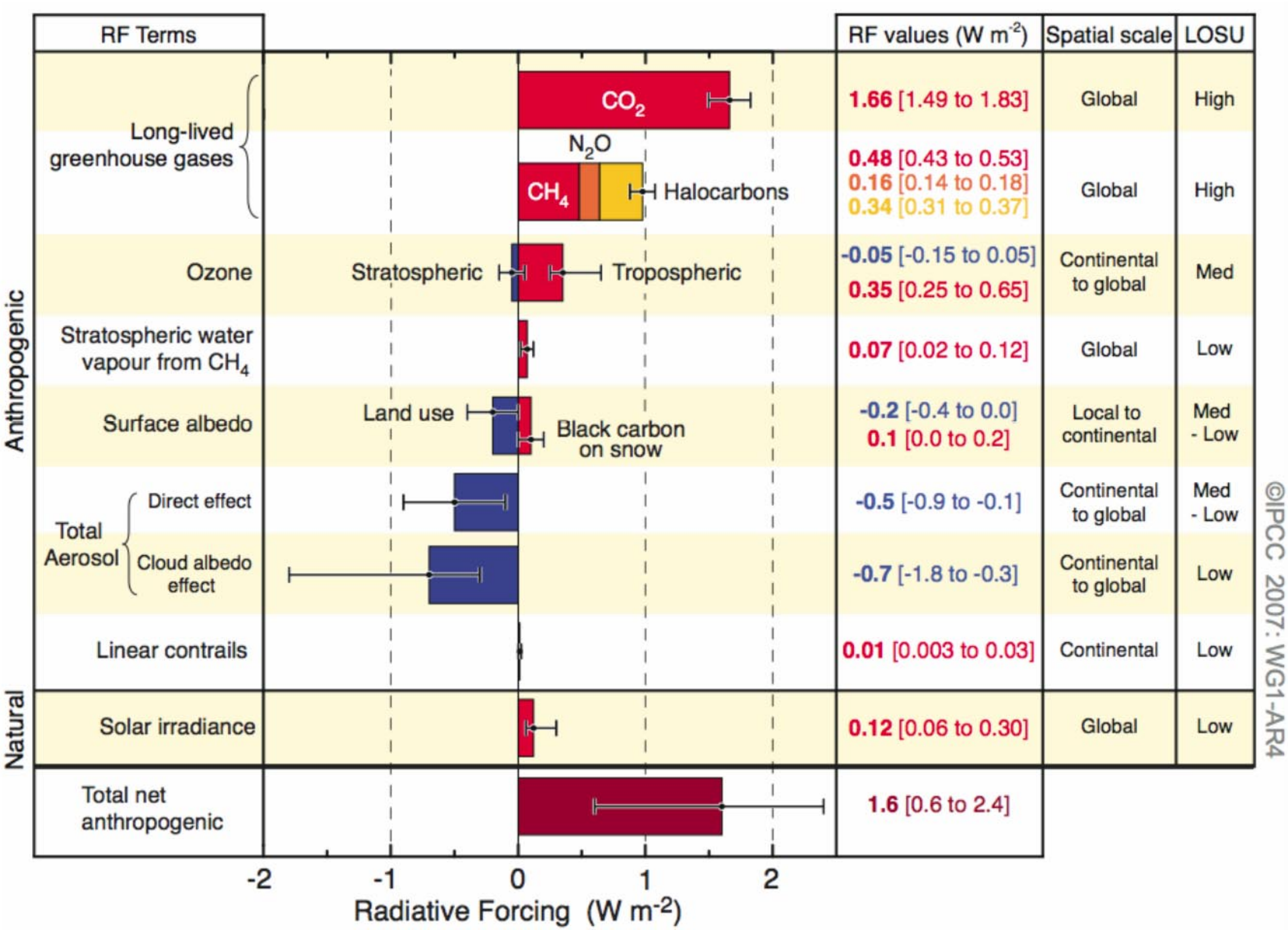
WHY IS THIS IMPORTANT?

Limits on use of fossil fuel.

The present factor of 2 uncertainty in climate sensitivity translates roughly into a ***factor of 2 uncertainty in how much carbon can be used for energy for a given effect on climate***.

GLOBAL-MEAN FORCINGS

Pre-industrial to present (IPCC, SPM, 2007)



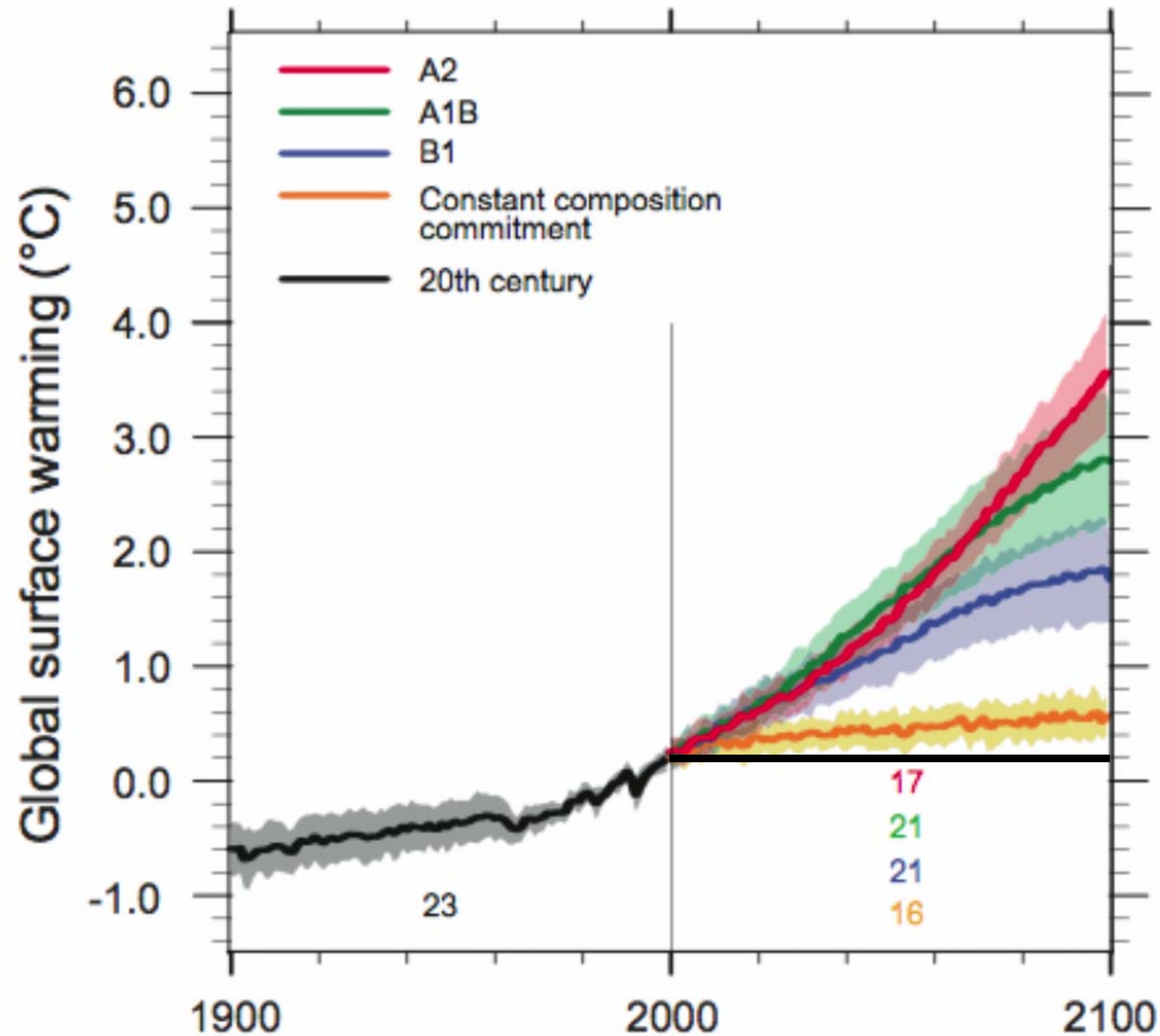
WHY IS THIS IMPORTANT?

Empirical inference of climate sensitivity.

Evaluation of the performance of climate models over the industrial period.

COMMITTED WARMING IN CLIMATE MODEL RUNS

Atmospheric composition held constant at 2000 value (IPCC, 2007)



Temperature increase for constant composition is “committed warming.”

"COMMITTED WARMING," "THERMAL INERTIA," "WARMING IN THE PIPELINE"

" ***Additional global warming of ... 0.6˚C is "in the pipeline"*** and will occur in the future even if atmospheric composition and other climate forcings remain fixed at today's values.

Hansen et al, Science, 2005

" Even if the concentrations of greenhouse gases in the atmosphere had been stabilized in the year 2000, we are already ***committed to further global warming of about another half degree***.

Meehl, Washington, et al., Science, 2005

" Even if atmospheric composition were fixed today, global-mean temperature ... rise would continue due to ***oceanic thermal inertia***. The ***warming commitment could exceed 1˚C***.

Wigley, Science, 2005

“COMMITTED WARMING,” “THERMAL INERTIA,” “WARMING IN THE PIPELINE” (*cont’d*)

“Because of the long time scale required for removal of CO_2 from the atmosphere as well as the time delays characteristic of physical responses of the climate system, global mean temperatures are expected to increase by ***several tenths of a degree*** for at least the next 20 years even if CO_2 emissions were immediately cut to zero; that is, there is a ***commitment to additional*** $\boldsymbol{CO_2}$***-induced warming*** even in the absence of emissions.

Friedlingstein and Solomon, PNAS, 2005

WHY IS THIS IMPORTANT?

Knowledge about "committed warming" or "warming in the pipeline."

ENERGY BALANCE MODELS

STOVE-TOP MODEL OF EARTH'S CLIMATE SYSTEM

STOVE-TOP MODEL OF EARTH'S CLIMATE SYSTEM

$$\frac{dH}{dt} = C\frac{dT}{dt} = Q - k(T - T_{\text{amb}})$$

H = heat content T = temperature

C = system heat capacity

Q = heating rate from stove

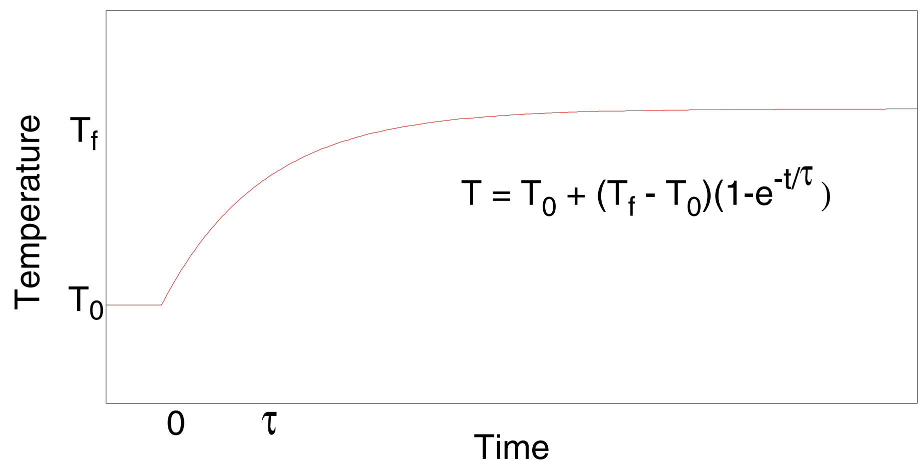
T_{amb} = ambient temperature

Steady State T: $T_\infty = T_{\text{amb}} + \frac{Q}{k}$

let $Q \rightarrow Q + F$: $\Delta T_\infty = \frac{F}{k}$

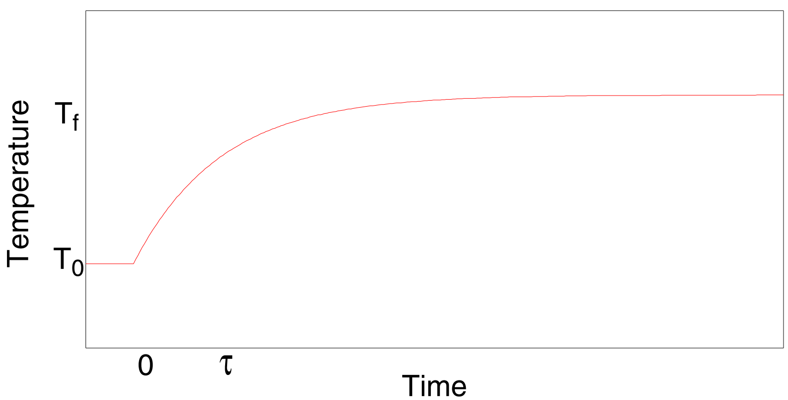
Sensitivity: $\lambda^{-1} \equiv \frac{\Delta T_\infty}{F} = \frac{1}{k}$

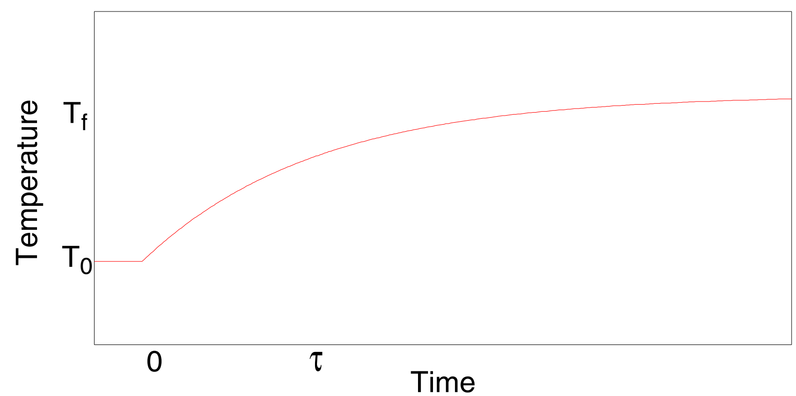
Time constant: $\tau = C\lambda^{-1}$



τ is the time constant of the system response to a perturbation.

DEPENDENCE OF RESPONSE ON SYSTEM HEAT CAPACITY





For constant k, ΔT_∞ and λ^{-1} are independent of system heat capacity C.

Time constant τ varies linearly with heat capacity: $\tau = C\lambda^{-1}$

Sensitivity can be inferred from τ and C as $\lambda^{-1} = \tau / C$.

BILLIARD BALL MODEL OF EARTH’S CLIMATE SYSTEM

BILLIARD BALL TEMPERATURE SENSITIVITY AND TIME CONSTANT

Evaluated according to the Stefan-Boltzmann radiation law

Energy balance: $\dfrac{dH}{dt} = Q - E = Q - \sigma T^4$

Initially $Q_0 = \sigma T_0^4$

Temperature sensitivity: $\Delta T_{\mathrm{ss}} = \lambda^{-1} \Delta Q$; $\Delta T(t) = \lambda^{-1} \Delta Q (1 - e^{-t/\tau})$

For Stefan-Boltzmann planet sensitivity is $\lambda^{-1}_{\text{S-B}} = \dfrac{T}{4Q}$

Relaxation time constant is $\tau_{\text{S-B}} = \dfrac{TC}{4Q} = C\lambda^{-1}_{\text{S-B}}$

BILLIARD BALL TEMPERATURE SENSITIVITY

Evaluated according to the Stefan-Boltzmann radiation law

For $Q_0 = \gamma S_0 / 4$ where S_0 is the solar constant = 1370 W m^{-2}
and γ is global mean co-albedo = 0.69

Climate sensitivity is $\lambda^{-1}_{\text{S-B}}$ = 0.27 K/(W m^{-2})

For $2 \times CO_2$ forcing $F_{2\times}$ = 3.71 W m^{-2}, $\Delta T_{2\times}$ = 1.0 K

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

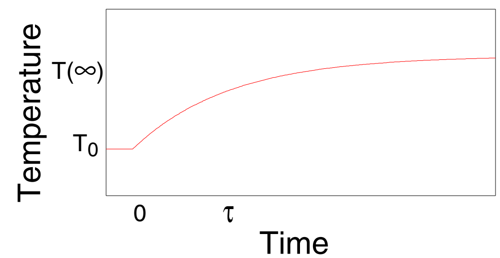
γ is planetary co-albedo

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" $\Delta T_S(\infty) = \lambda^{-1} F$

λ^{-1} is equilibrium climate sensitivity $\lambda^{-1} = f \dfrac{T_0}{4\gamma_0 J_S}$ K / (W m^{-2})

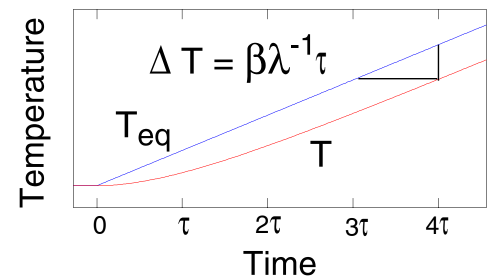
f is feedback factor $$f = \left(1 - \frac{1}{4}\frac{d\ln\gamma}{d\ln T}\bigg|_0 + \frac{1}{4}\frac{d\ln\varepsilon}{d\ln T}\bigg|_0\right)^{-1}$$

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

τ is climate system time constant $\tau = C\lambda^{-1}$ or $\lambda^{-1} = \tau / C$

TEMPERATURE RESPONSE TO LINEARLY INCREASING FORCING

$$\beta = d\text{forcing}/d\text{time}$$



Energy balance: $$C\frac{dT_S}{dt} = \beta t + \gamma J_S - \varepsilon\sigma T_S^4$$

Time-dependence: $$\Delta T_S(t) = \beta\lambda^{-1}[(t-\tau) + \tau e^{-t/\tau}]$$

λ^{-1} and τ are the same as before: $$\lambda^{-1} = \tau / C$$

For $t/\tau \gtrsim 3$, $$\Delta T_S(t) = \beta\lambda^{-1}(t-\tau)$$

Temperature lags equilibrium response by: $$\Delta T_{lag} = \beta\lambda^{-1}\tau$$

DETERMINING EARTH'S HEAT CAPACITY BY OCEAN CALORIMETRY

HEAT CAPACITY OF EARTH'S CLIMATE SYSTEM FROM GLOBAL MEAN HEAT CONTENT AND SURFACE TEMPERATURE TRENDS

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

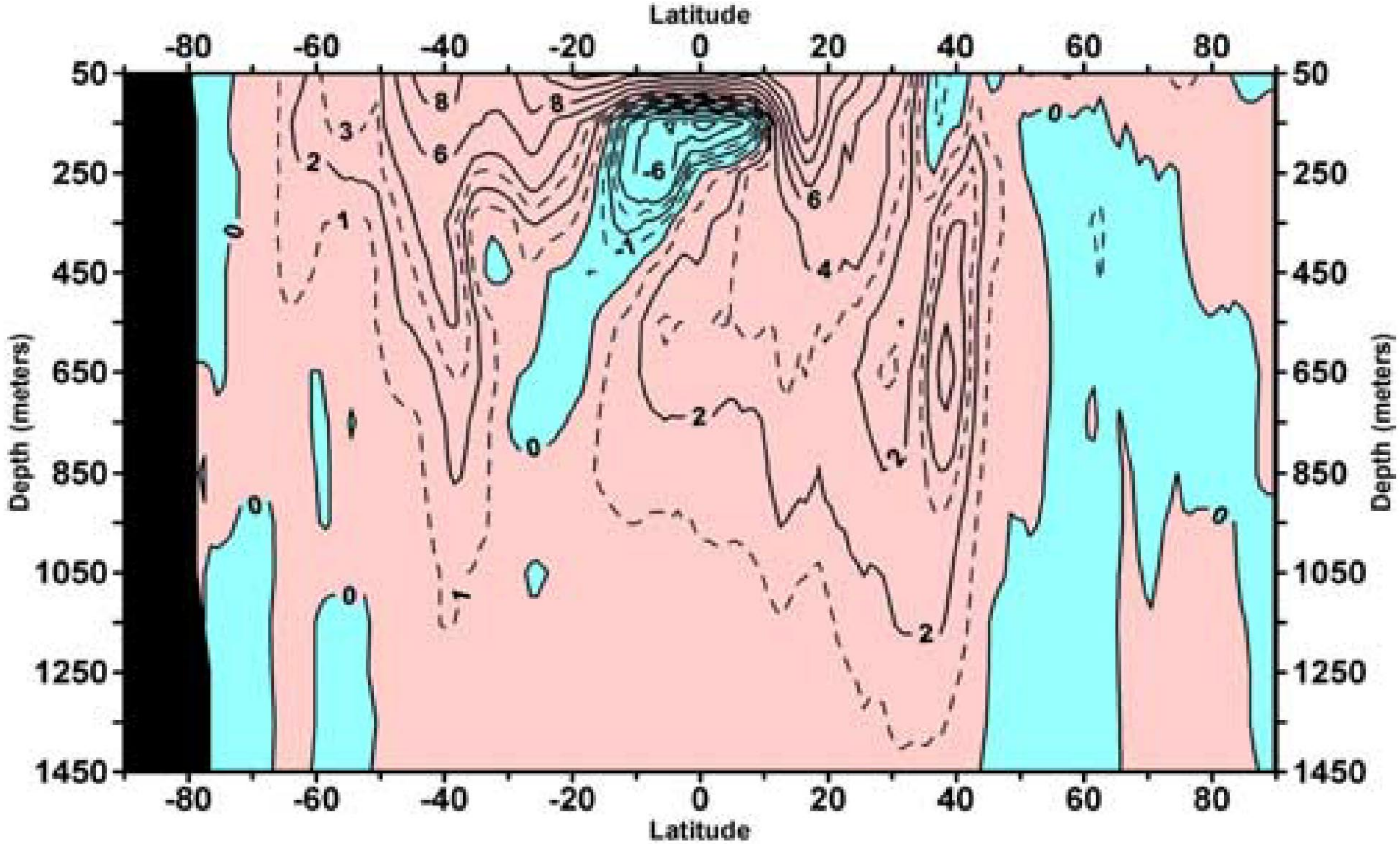
C: Global heat capacity

H: Global ocean heat content

T_S: Global mean surface temperature

ZONAL AVERAGE HEAT CONTENT TREND (1955-2003)

10^{18} J (100 m)$^{-1}$ (1° latitude)$^{-1}$ yr^{-1}



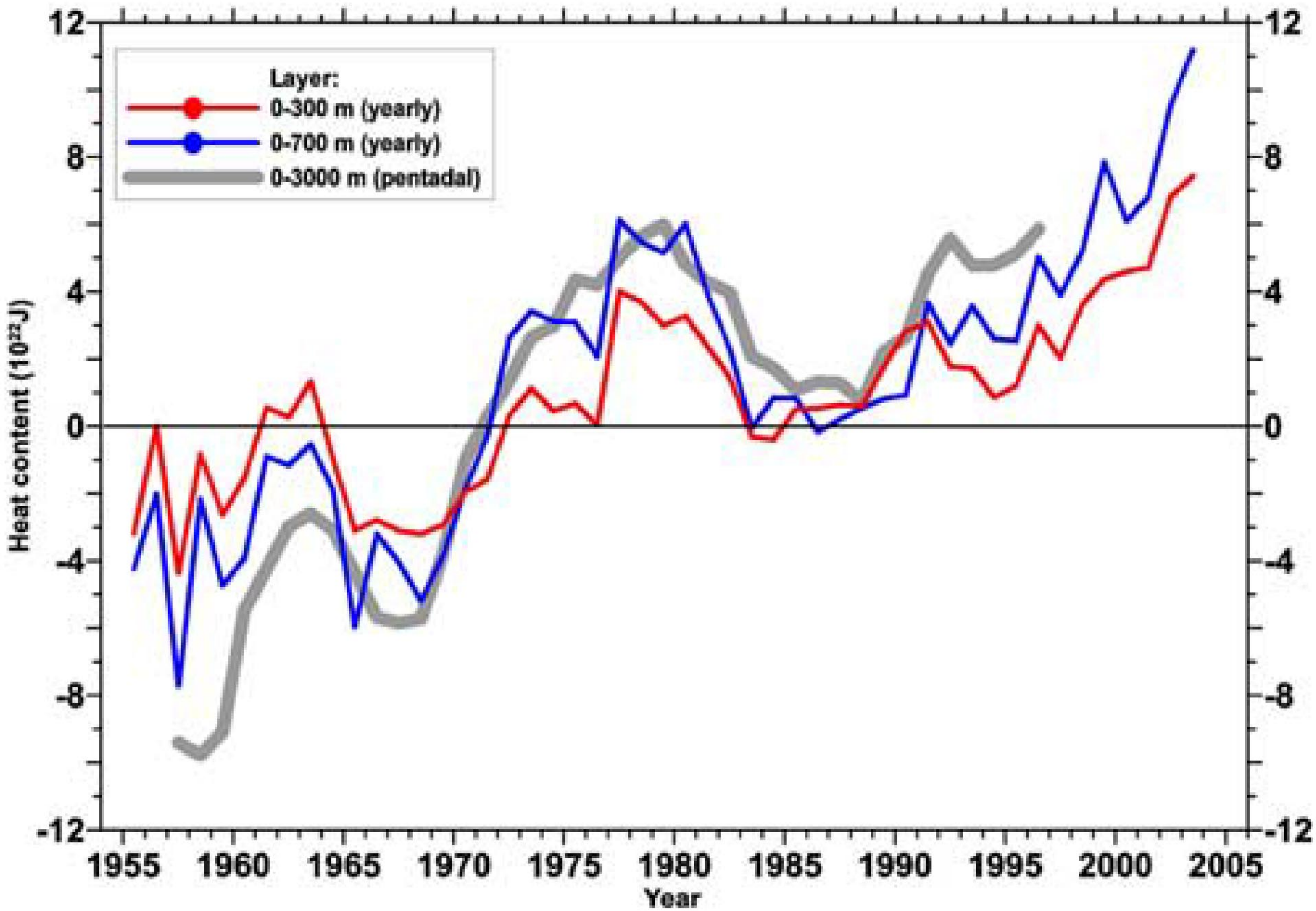
- Heating is greatest in upper ocean, with downwelling plumes.

Warming of the world ocean, 1955–2003

S. Levitus, J. Antonov, and T. Boyer

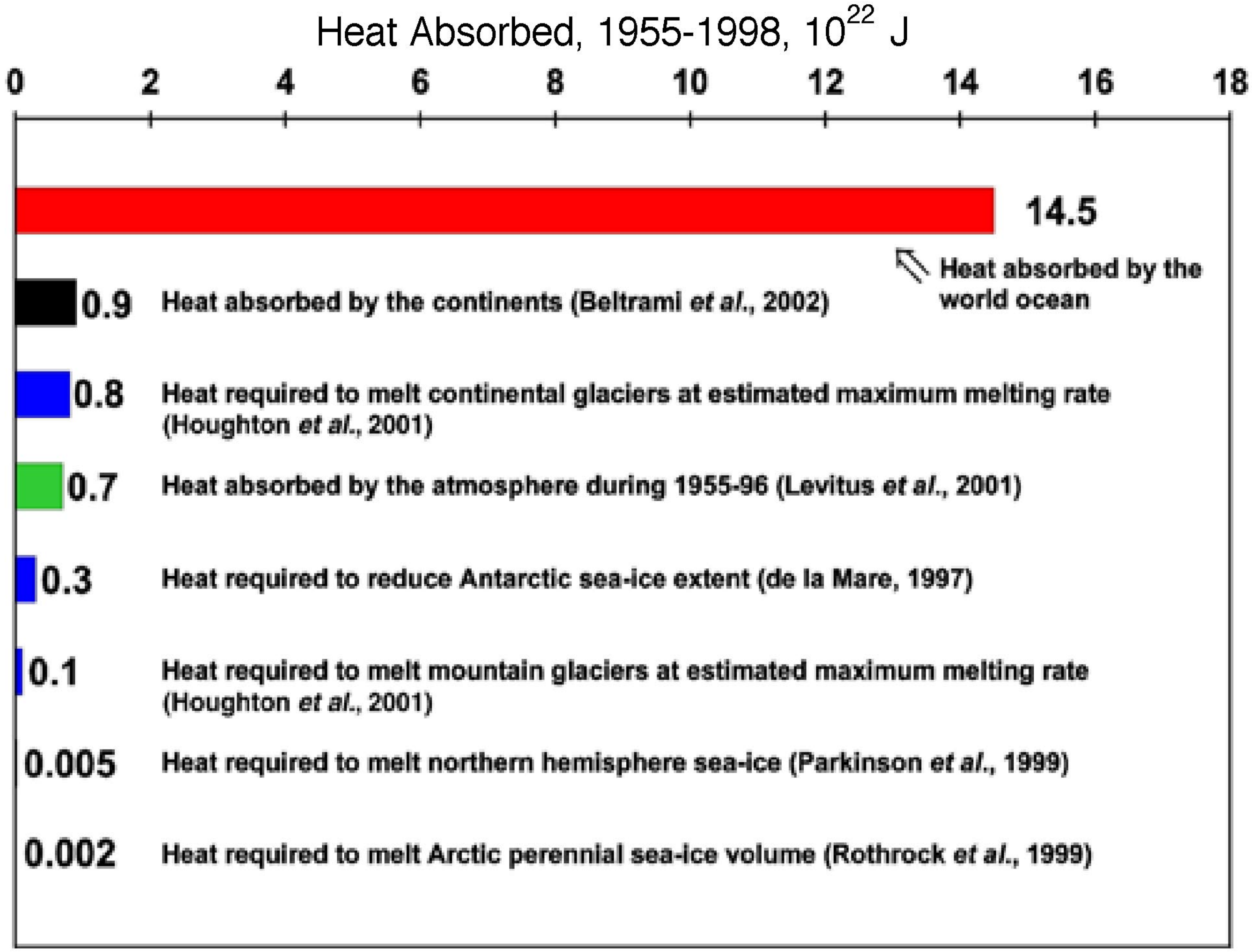
GEOPHYSICAL RESEARCH LETTERS, VOL. 32, 2005

HEAT CONTENT OF WORLD OCEANS, 10^{22} J



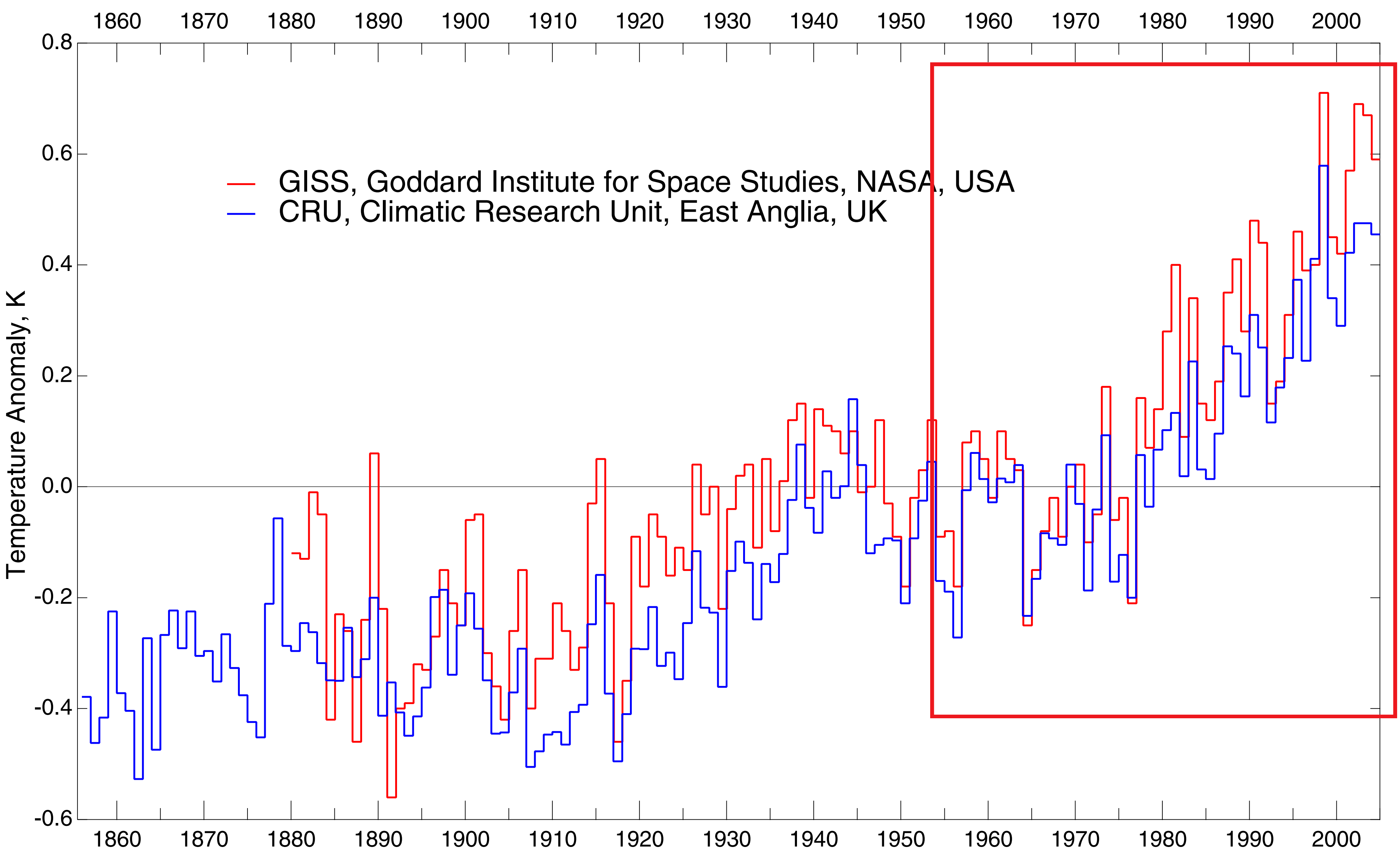
Levitus et al., 2005

HEAT ABSORPTION BY COMPONENTS OF EARTH'S CLIMATE SYSTEM



The world ocean is responsible for ~84% of the increase in global heat content. *Levitus et al., 2005*

GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD



DIRECT DETERMINATION OF EARTH'S HEAT CAPACITY

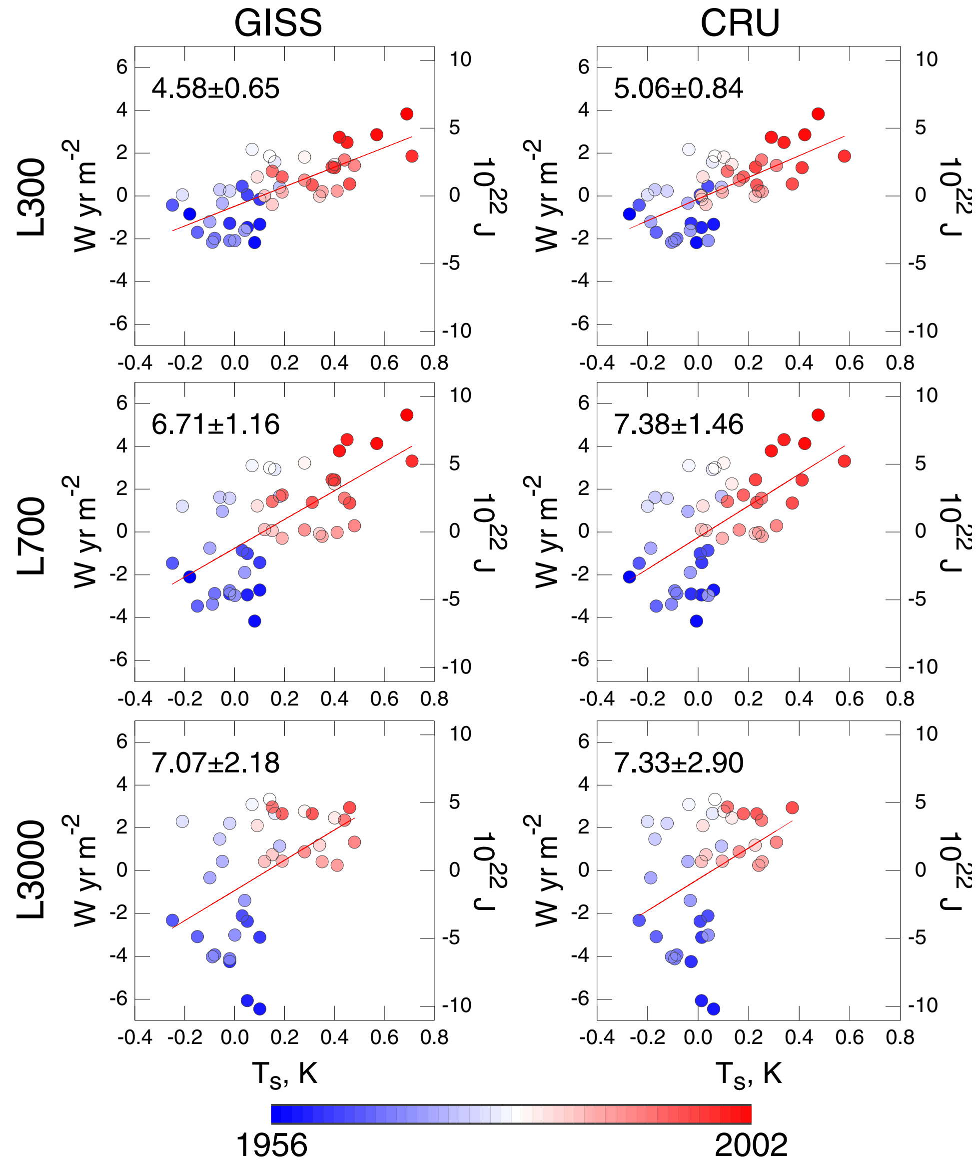
$$C = dH \,/\, dT_s$$

Global heat content *H* from Levitus et al., *GRL*, 2005.

L300: Surface to 300 m
L700: Surface to 700 m
L3000: Surface to 3000 m

Global mean surface temperature T_s from Goddard Institute of Space Sciences (GISS) and Climatic Research Unit (CRU).

Slope gives heat capacity:
7.1 ± 2 W yr m^{-2} K^{-1}
(≈ 76 m @ 71% ocean fraction)

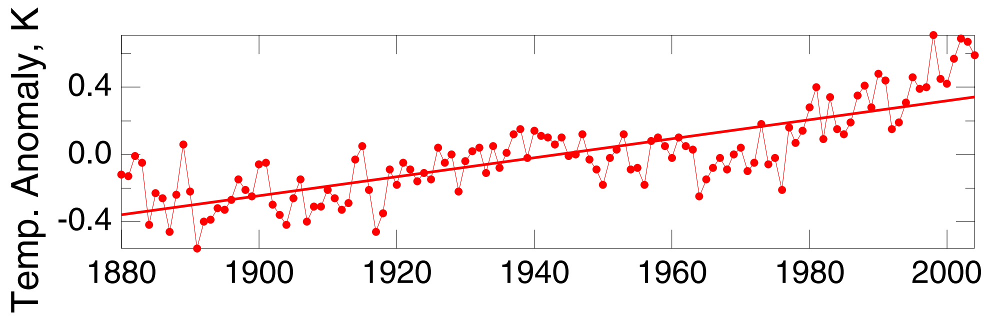


- 65-70% of heat capacity is between surface and 300 m.
- Other heat sinks raise global heat capacity to 8.5 ± 2.4 W yr m^{-2} K^{-1}.

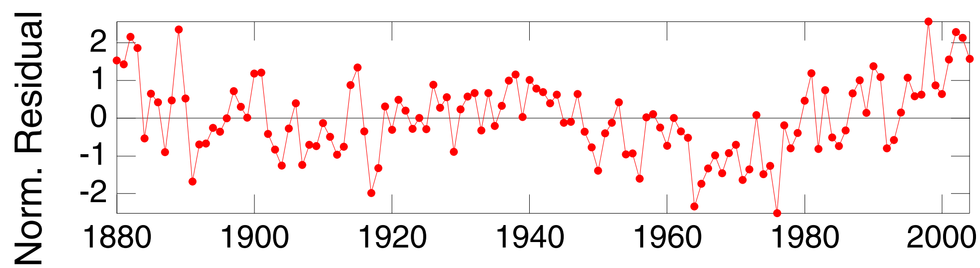
CHARACTERISTIC TIME OF EARTH'S CLIMATE SYSTEM FROM TIME SERIES ANALYSIS

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

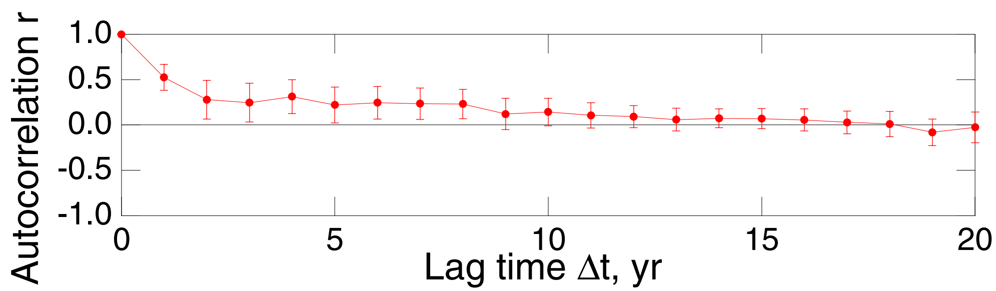
Recipe (GISS annual global mean surface temperature anomaly T_s)



1. Remove long term trend; plot the residuals:

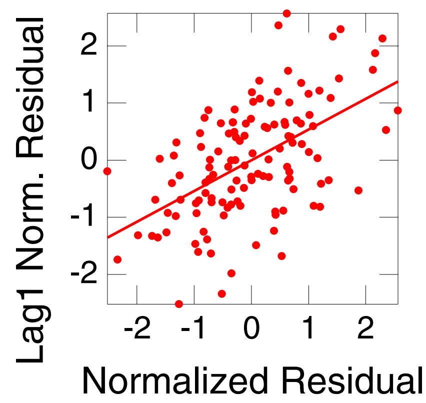


2. Calculate autocorrelogram (& standard deviations; Bartlett, 1948):

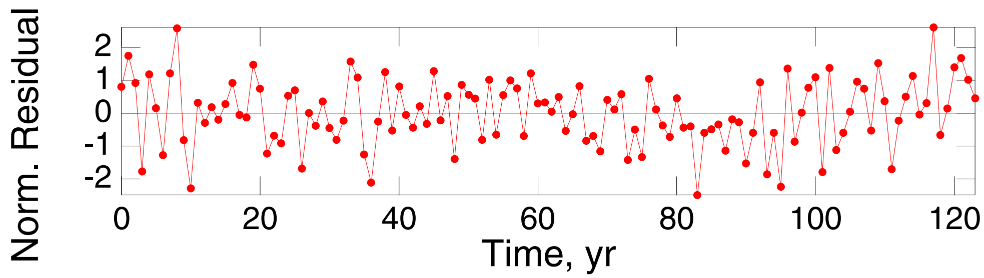


Recipe for determining climate system time constant, continued

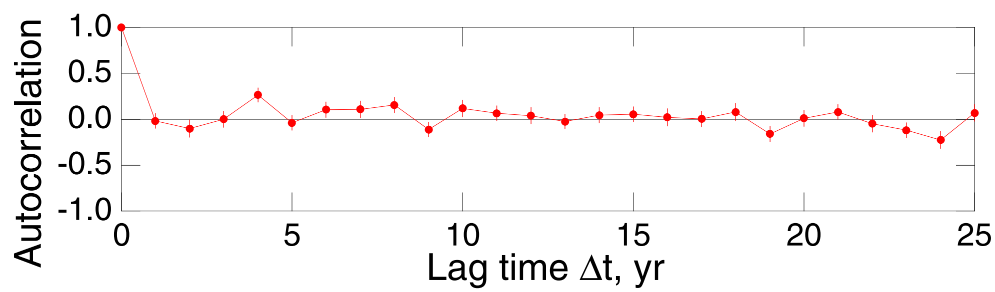
3. Examine the *lag*-1 autocorrelation:



4. Remove the trend; plot the residuals:



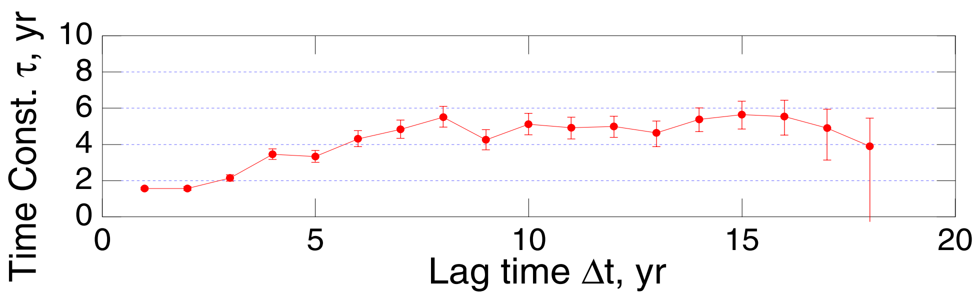
5. Examine for any remaining autocorrelation:



Recipe for determining climate system time constant, continued

6. If no residual autocorrelation (Markov process) calculate time constant τ for relaxation of system to perturbation:

$$r(\Delta t) = e^{-\Delta t/\tau} \quad \text{or} \quad \tau(\Delta T) = -\Delta T \,/ \ln r(\Delta T) \qquad \text{(Leith, 1973)}$$



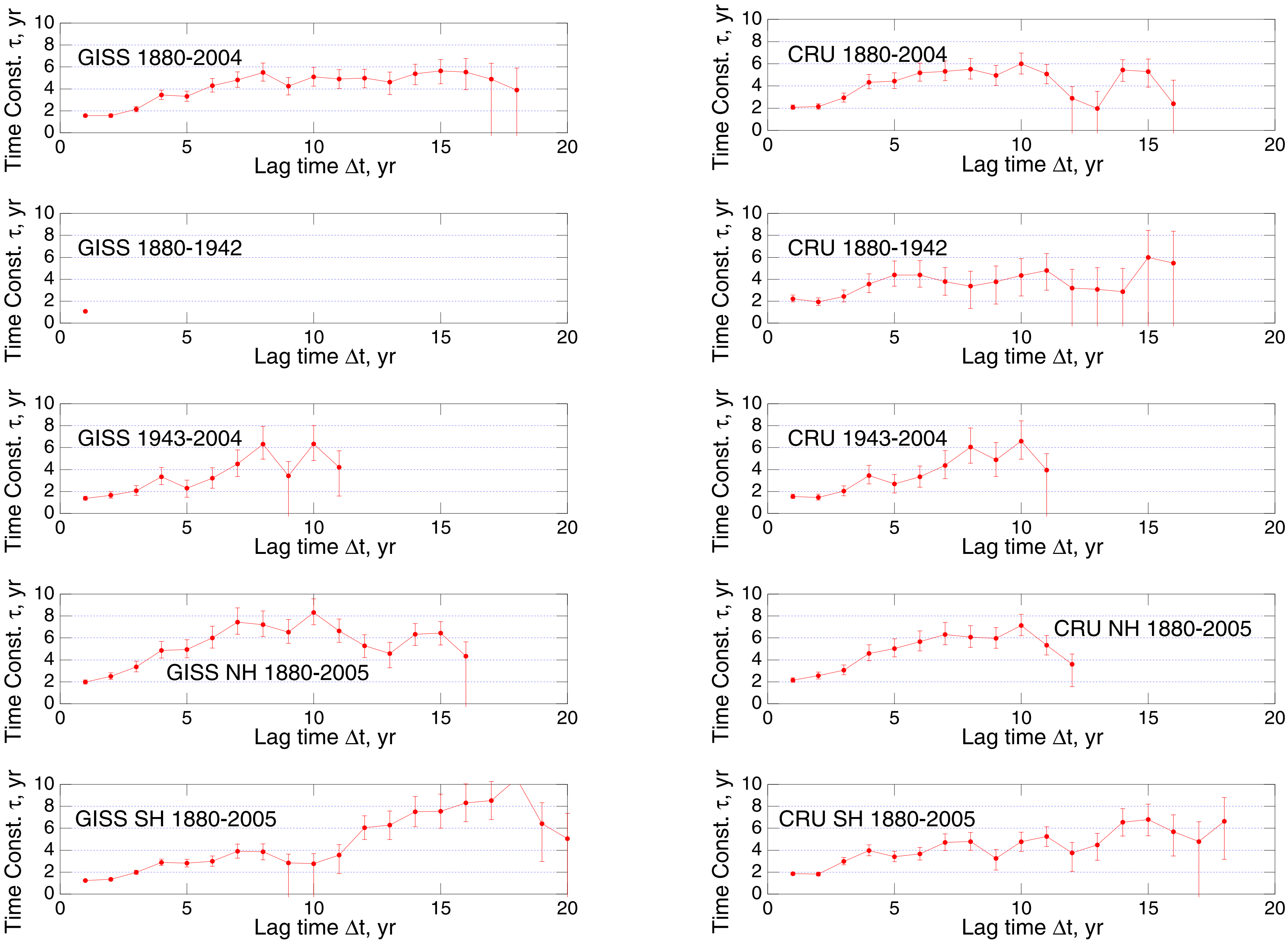
- Time constant τ ***increases with increasing lag time***.

- Implies coupling of T_s to a system of longer time constant.

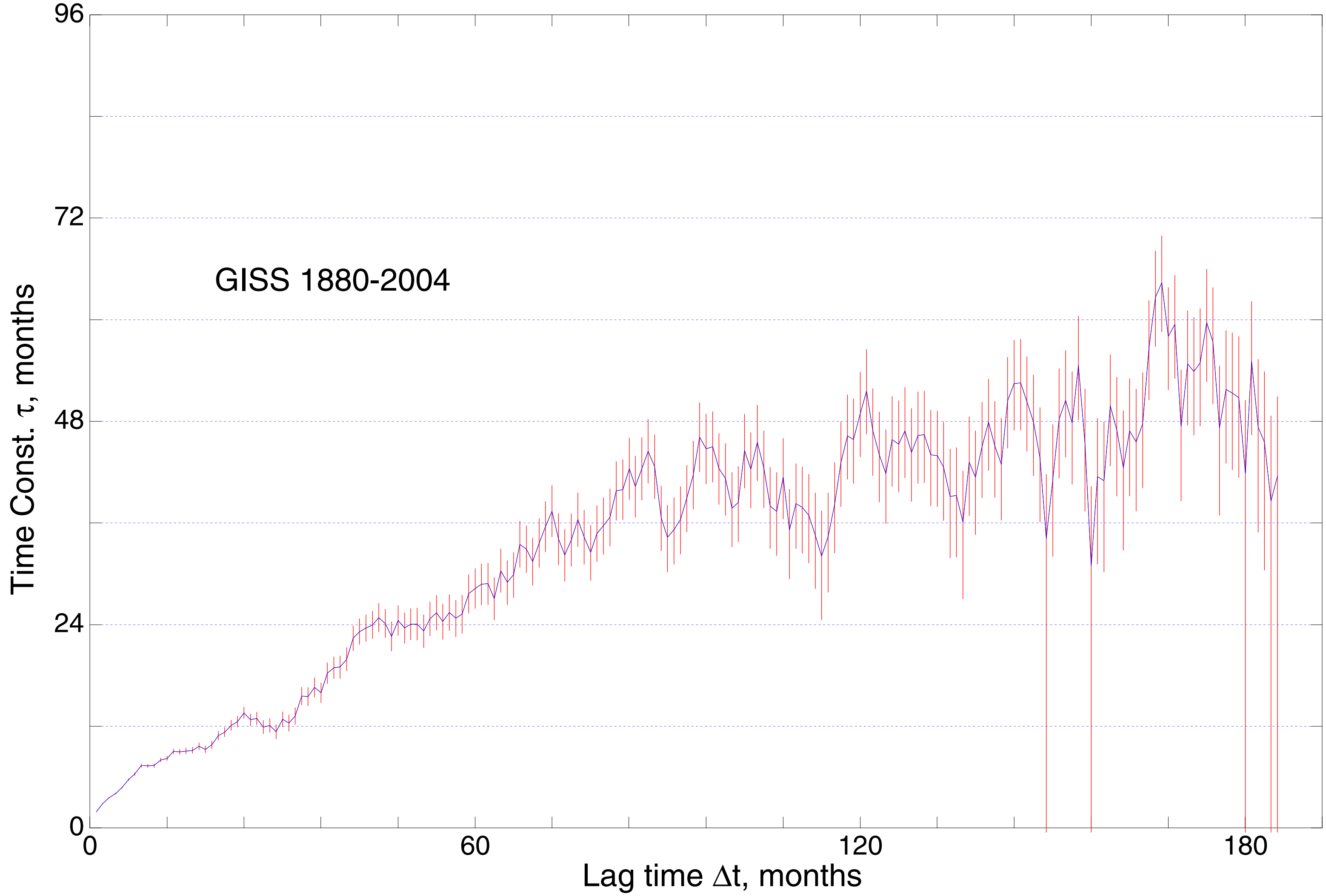
- On decadal scale time constant asymptotes to 5 ± 1 yr.

- This is the ***e-folding time constant*** for relaxation of global mean surface temperature to perturbations on the decadal scale.

THIS RESULT IS ROBUST



SAME RESULT WITH DESEASONALIZED MONTHLY DATA



- Again the time constant is about 5 yr.

CLIMATE SENSITIVITY

Equilibrium climate sensitivity $\lambda^{-1} = \tau / C$

- Time constant $\tau = 5 \pm 1$ yr
- Heat capacity $C = 8.5 \pm 2.4$ W yr m^{-2} K^{-1}
- Sensitivity $\lambda^{-1} = 0.59 \pm 0.20$ K / (W m^{-2})
- Sensitivity to forcing by $2 \times CO_2$

For $F_{2\times} = 3.7$ W m^{-2} $\Delta T_{2\times} = 2.2 \pm 0.75$ K

Compare IPCC AR3 (2001): $\Delta T_{2\times} = 1.5 - 4.5$ K

IPCC AR4 (2007): $\Delta T_{2\times} = 2.0 - 4.5$ K

INFERRED FORCING (1900 – 2000)

Forcing $F = \Delta T / \lambda^{-1}$

- Temperature change $\Delta T = 0.57 \pm 0.08$ K (Folland, 2001)
- Sensitivity $\lambda^{-1} = 0.59 \pm 0.20$ K / (W m^{-2})
- Total forcing $F_{\text{Total}} = 0.97 \pm 0.36$ W m^{-2}

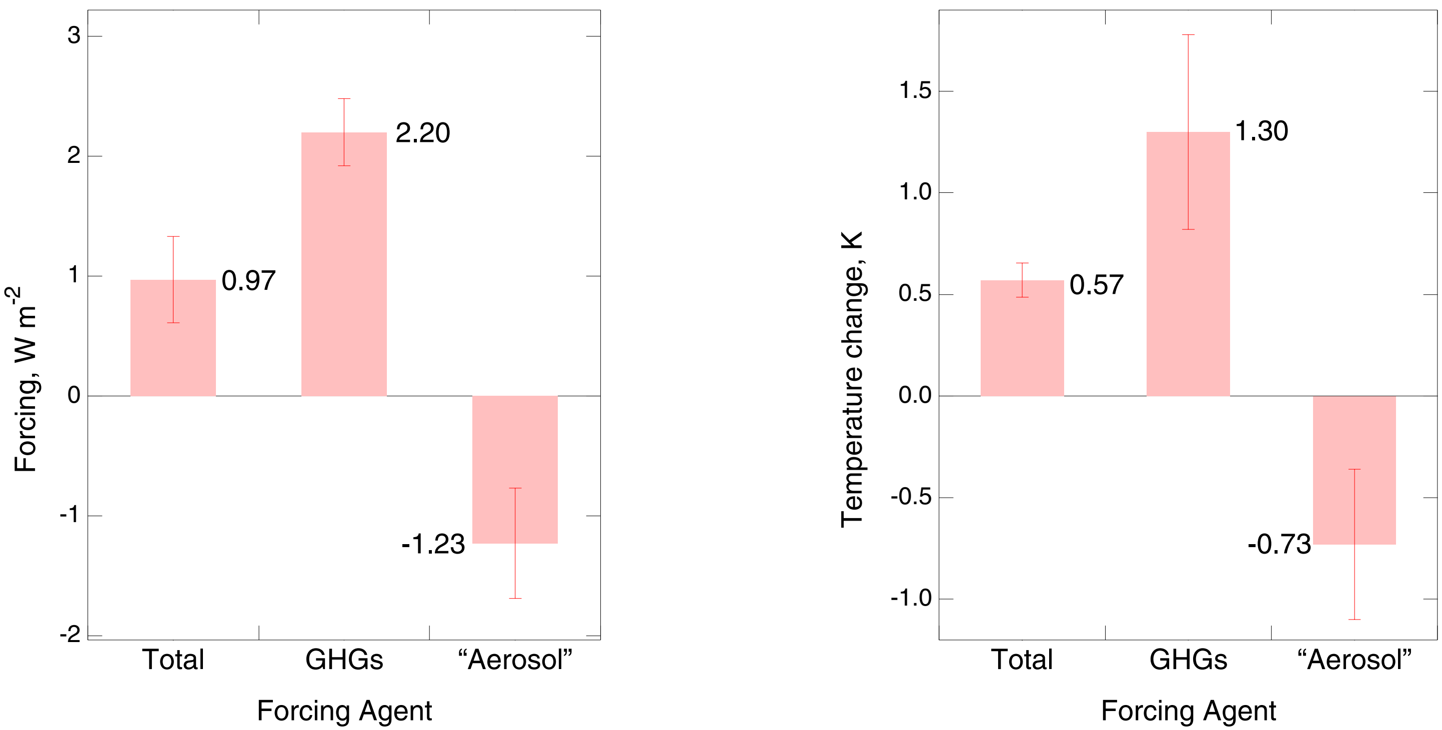
"AEROSOL" FORCING (1900 – 2000)

Inverse calculation

$$F_{\text{Aerosol}} = F_{\text{Total}} - F_{\text{GHG}}$$

- Total forcing $F_{\text{Total}} = 0.97 \pm 0.36$ W m^{-2}
- Greenhouse gas forcing $F_{\text{GHG}} = 2.2 \pm 0.28$ (IPCC, 2001)
  WMGG; tropospheric, stratospheric O_3
- "Aerosol" forcing $F_{\text{Aerosol}} = -1.23 \mp 0.46$ W m^{-2}

INVERSE CALCULATION OF "AEROSOL" FORCING AND ATTRIBUTION OF TEMPERATURE CHANGE (1900 - 2000)



- "Aerosol" forcing is calculated as difference between empirically determined total forcing and greenhouse gas forcing (long lived GHGs, tropospheric and stratospheric O_3).
- Temperature change is calculated from empirically determined sensitivity, distributed according to forcings.

HOW MUCH DOES TEMPERATURE LAG THE FORCING?

Temperature response lags forcing by time τ.

What is the temperature lag?

$$\Delta T_{\text{lag}} = \beta \lambda^{-1} \tau$$

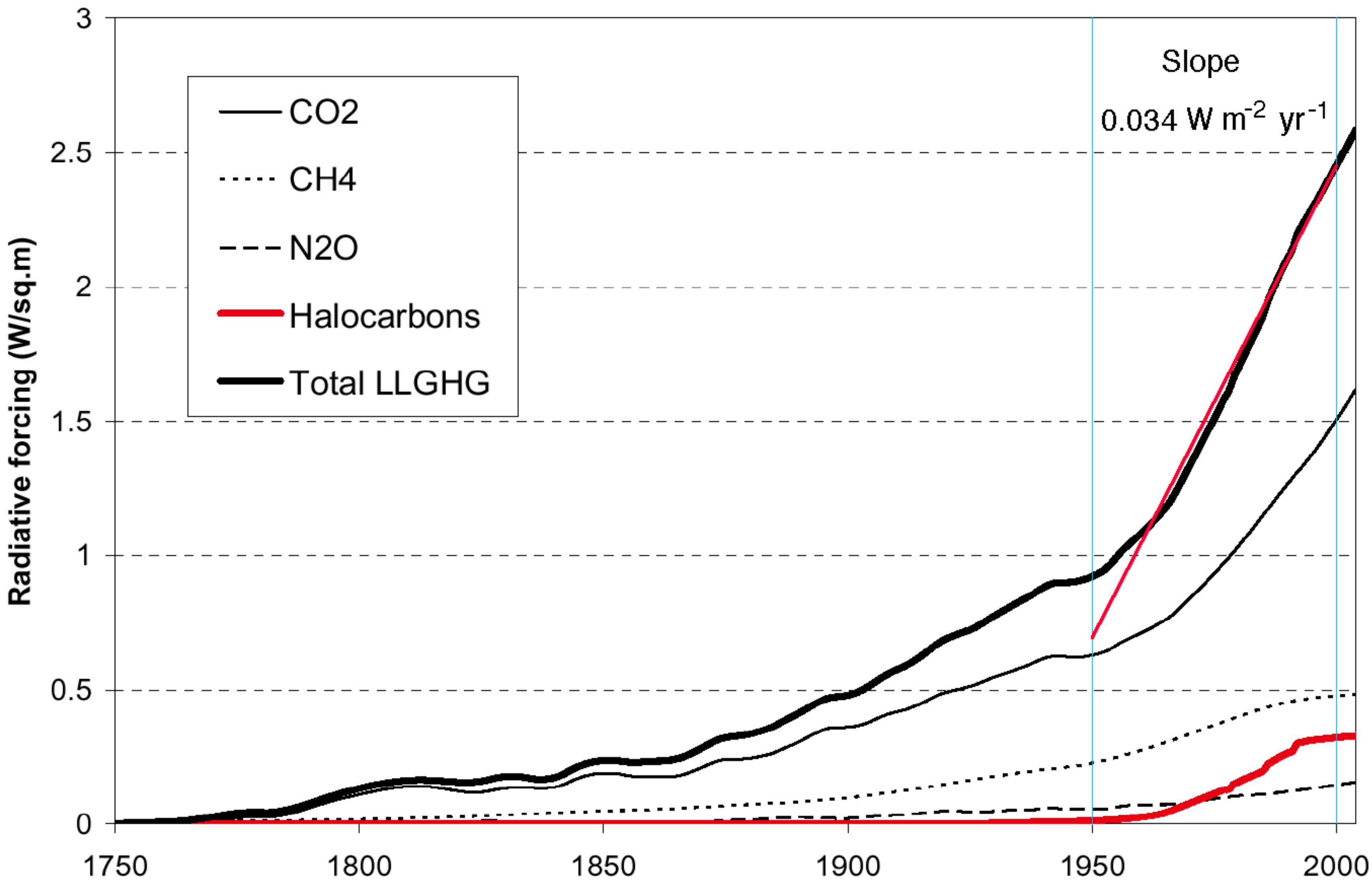
$\tau = 5$ yr

$\lambda^{-1} = 0.59$ K/(W m^{-2})

Recall $\beta = \dfrac{dF}{dt}$

RADIATIVE FORCING BY LONG-LIVED GREENHOUSE GASES

Pre-industrial to present (IPCC, 2007)



HOW MUCH DOES TEMPERATURE LAG THE FORCING?

Temperature response lags forcing by τ.

$$\Delta T_{\mathrm{lag}} = \beta\lambda^{-1}\tau$$

$\tau = 5$ yr

$\lambda^{-1} = 0.59$ K/(W m^{-2})

$\beta = 0.034$ W m^{-2} yr^{-1}

$\Delta T_{\mathrm{lag}} = 0.1$ K

Committed warming (heating in the pipeline) is minimal!

SUMMARY

- Despite intense research Earth's climate sensitivity remains ***uncertain to at least a factor of 2***.
- Energy balance considerations and empirical observations may usefully refine sensitivity estimates.
- Climate sensitivity can be determined as time constant upon heat capacity.
- The ***time constant*** of Earth's climate system is 5 ± 1 years.
- Climate system response to greenhouse forcing is in ***near steady state***, with little further warming (due to present GH gases) "in the pipeline."
- The ***effective heat capacity*** of Earth's climate system is 8.5 ± 2.4 W yr m^{-2} $K^{-1} \approx 90$ m of the world ocean.
- The ***equilibrium sensitivity*** of Earth's climate system is 0.59 ± 0.20 K / (W m^{-2}); $\Delta T_{2\times} = 2.2 \pm 0.75$ K.

CONCLUDING OBSERVATIONS

- The ***time constant***, ***heat capacity*** and ***sensitivity*** of Earth's climate system are ***important integral properties*** that should be examined in model calculations as well as observations.

- The short time constant of climate change implies that ***changes in global mean surface temperature are additive***, just like forcings.

- The temperature increase due to present excess long-lived greenhouse gases over the industrial period is 1.43 ± 0.5 K, largely offset by the temperature decrease due to present excess aerosols, is close to or already exceeds the threshold for dangerous anthropogenic warming, 1 – 2 K.

CONCLUDING OBSERVATIONS (*cont'd*)

- Present excess atmospheric CO_2 is 100% of 38 years' fossil fuel emissions; present excess aerosols are 100% of 1 week's emissions.