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

Stephen E. Schwartz

BROOKHAVEN NATIONAL LABORATORY

Aerosols – properties, processes and climate

INTROP Interdisciplinary Tropospheric Research:
From the Laboratory to Global Change

An ESF Scientific Programme

EUROPEAN SCIENCE FOUNDATION

ACCENT
ATMOSPHERIC COMPOSITION CHANGE
THE EUROPEAN NETWORK OF EXCELLENCE

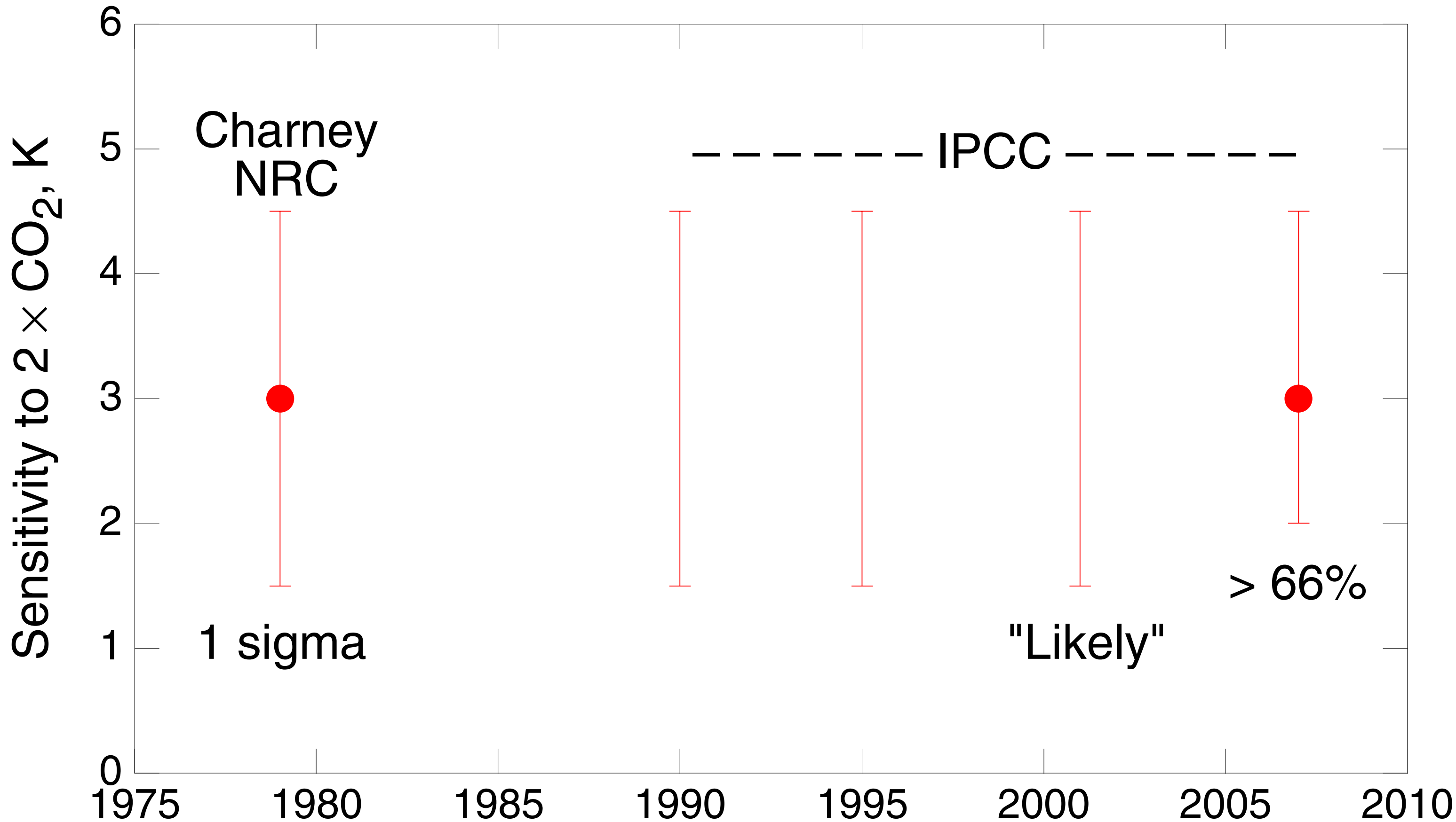
EUROCHAMP

Heraklion, Crete, Greece April 21 - 25, 2007

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

CLIMATE SENSITIVITY THROUGH THE AGES

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



FIRST ORDER QUESTIONS

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

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

What is the forcing F ?

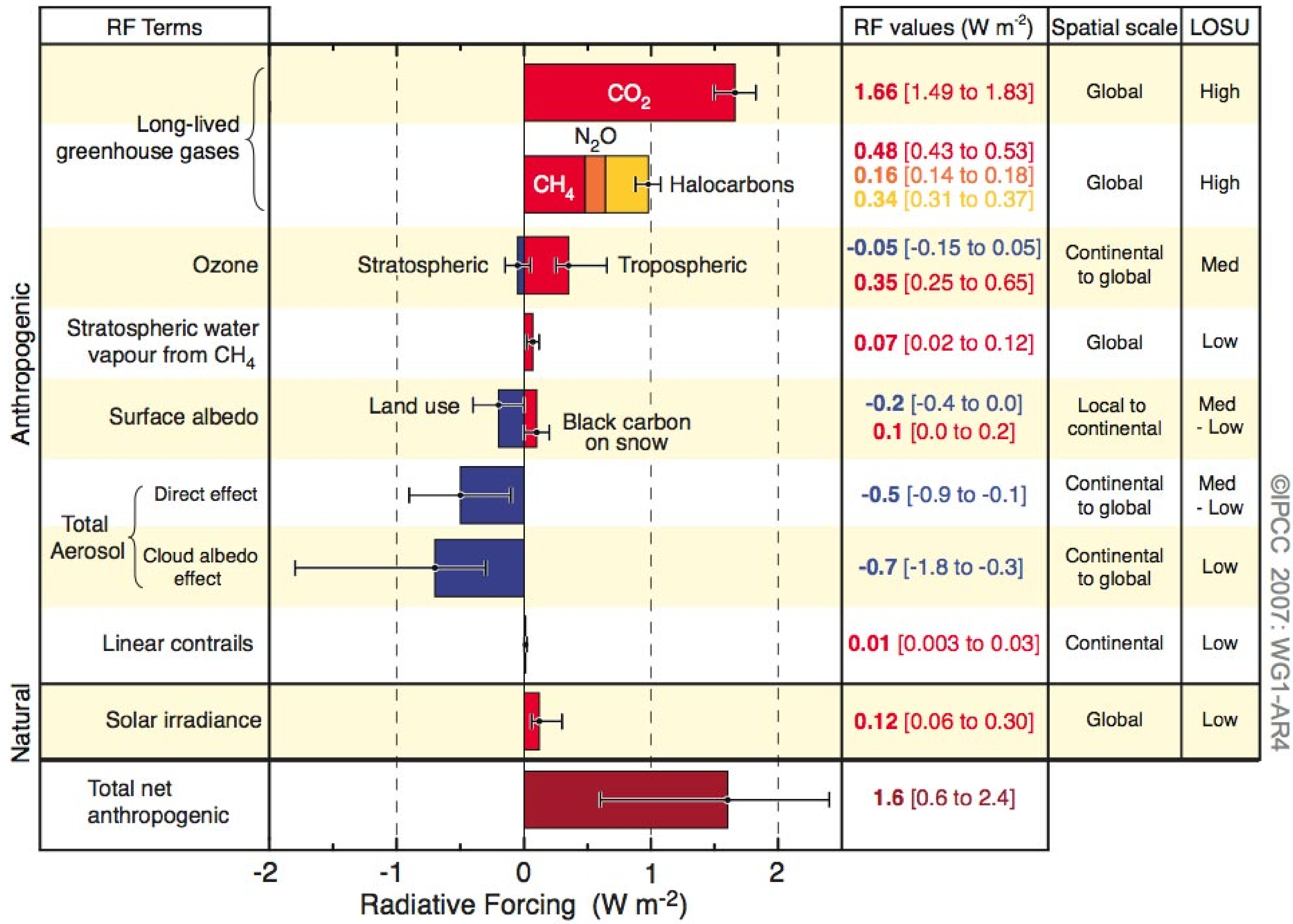
What is the equilibrium sensitivity λ^{-1} ?

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

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

GLOBAL-MEAN FORCINGS OF CLIMATE CHANGE

Pre-industrial to present (IPCC, Summary for Policymakers, 2007)



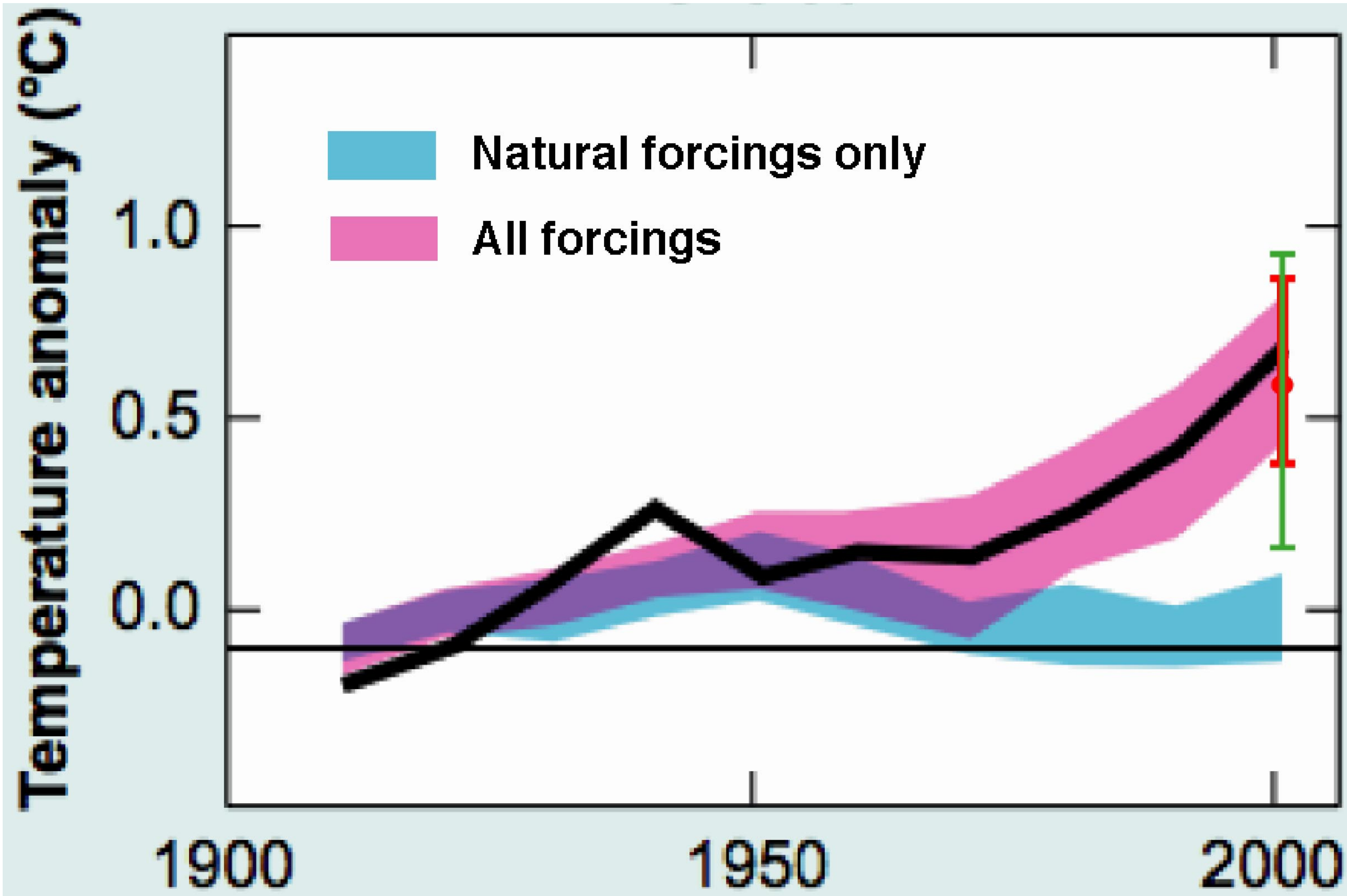
Aerosol forcings are greatest uncertainty in radiative forcing.

Total forcing estimates differ by more than a factor of 2 (5 - 95%).

This uncertainty may be an underestimate.

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models

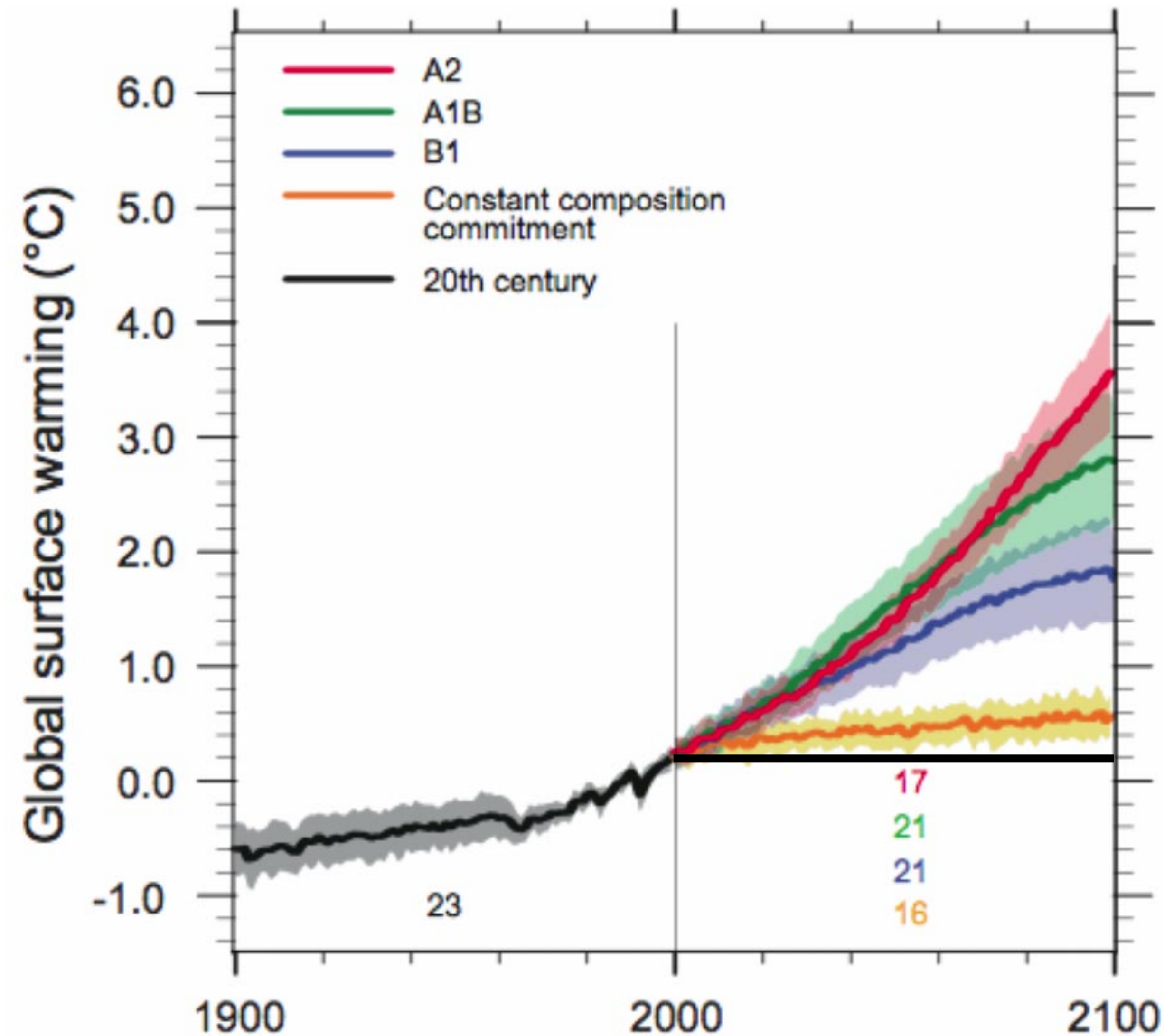


Modified from IPCC Summary for Policymakers, 2007

Spread in modeled temperature increase (less than a factor of 2, red) is well less than uncertainty in forcing (a factor of 4, green).

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 CO_2-induced warming*** even in the absence of emissions.

Friedlingstein and Solomon, PNAS, 2005

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

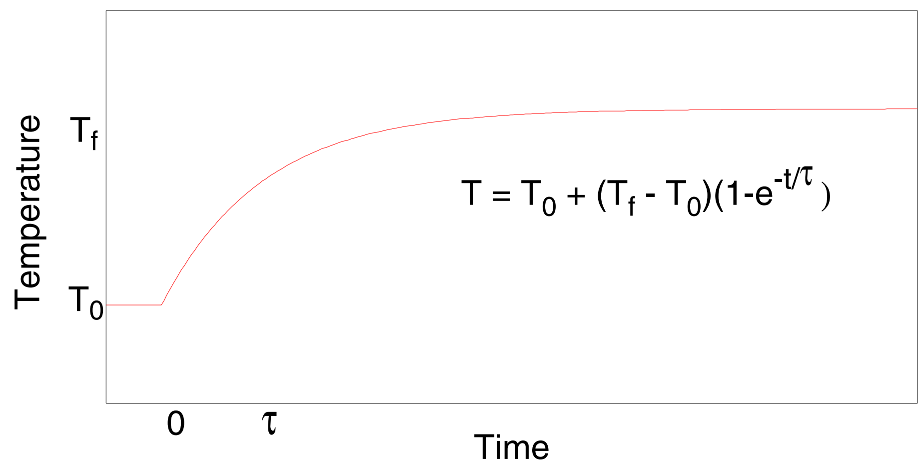
T_{amb} = ambient temperature

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

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

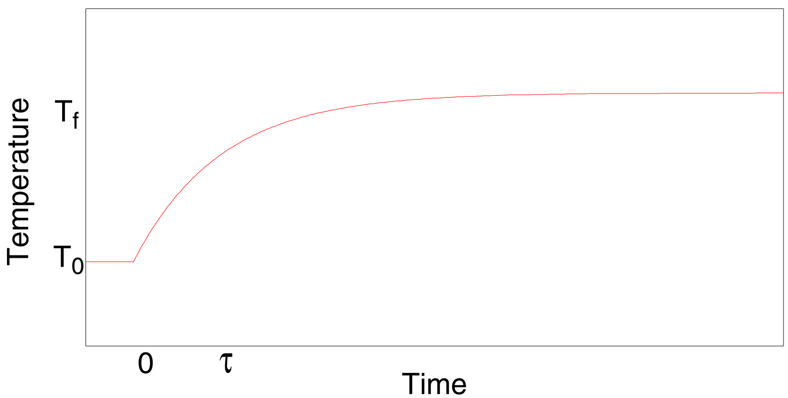
Sensitivity: $\lambda^{-1} \equiv \dfrac{\Delta T_\infty}{F} = \dfrac{1}{k}$

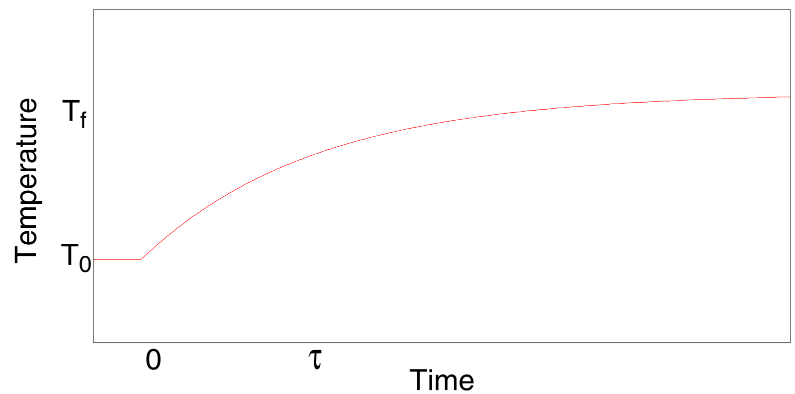
Time constant: $\tau = C\lambda^{-1}$



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

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 $\lambda^{-1}_{S\text{-}B}$ = 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

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

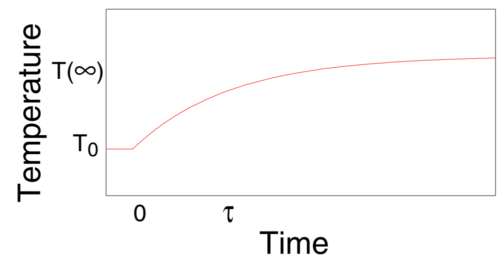
γ is planetary co-albedo

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})

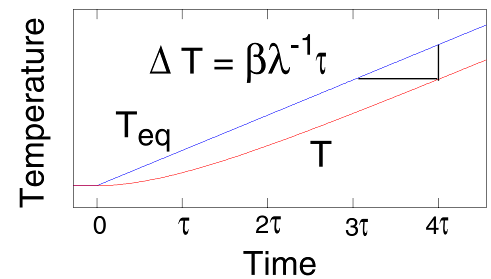
f is feedback factor $$f = \left(1 - \frac{1}{4}\frac{d\ln\gamma}{d\ln T}\bigg|_0 + \frac{1}{4}\frac{d\ln\varepsilon}{d\ln T}\bigg|_0\right)^{-1}$$

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

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

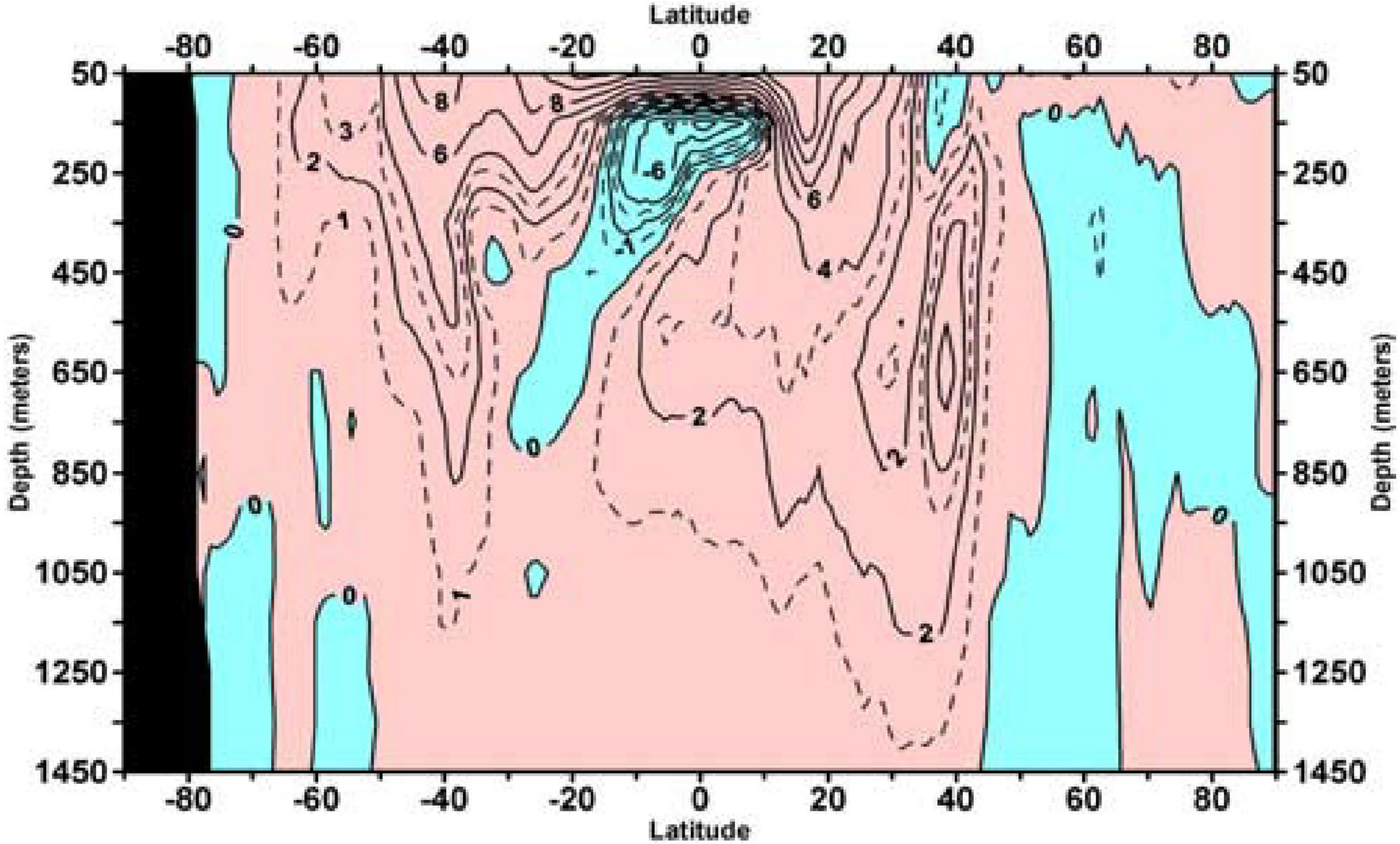
C: Global heat capacity

H: Global ocean heat content

T_S: Global mean surface temperature

ZONAL AVERAGE HEAT CONTENT TREND (1955-2003)

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



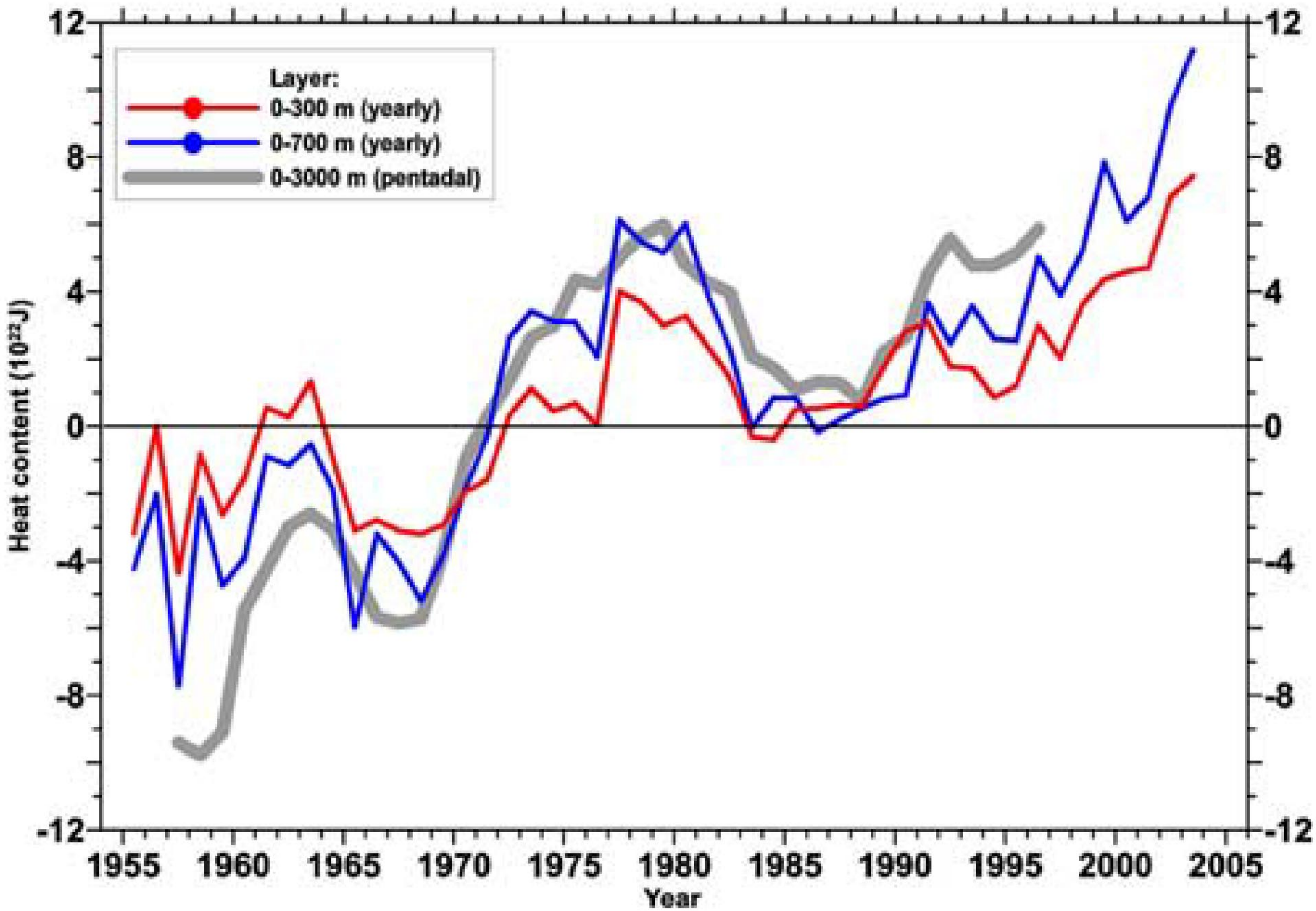
- Heating is greatest in upper ocean, with downwelling plumes.

Warming of the world ocean, 1955–2003

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

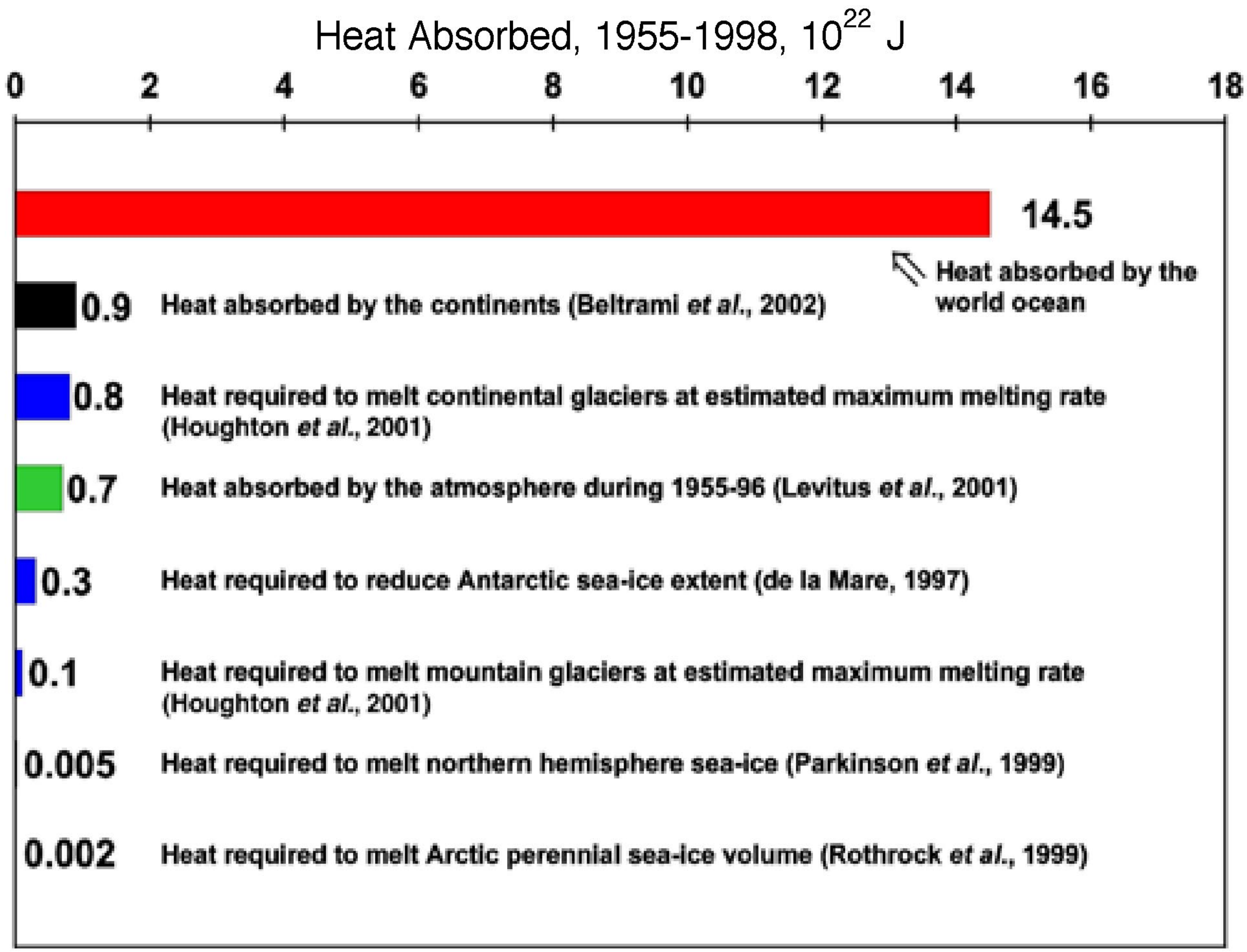
GEOPHYSICAL RESEARCH LETTERS, VOL. 32, 2005

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



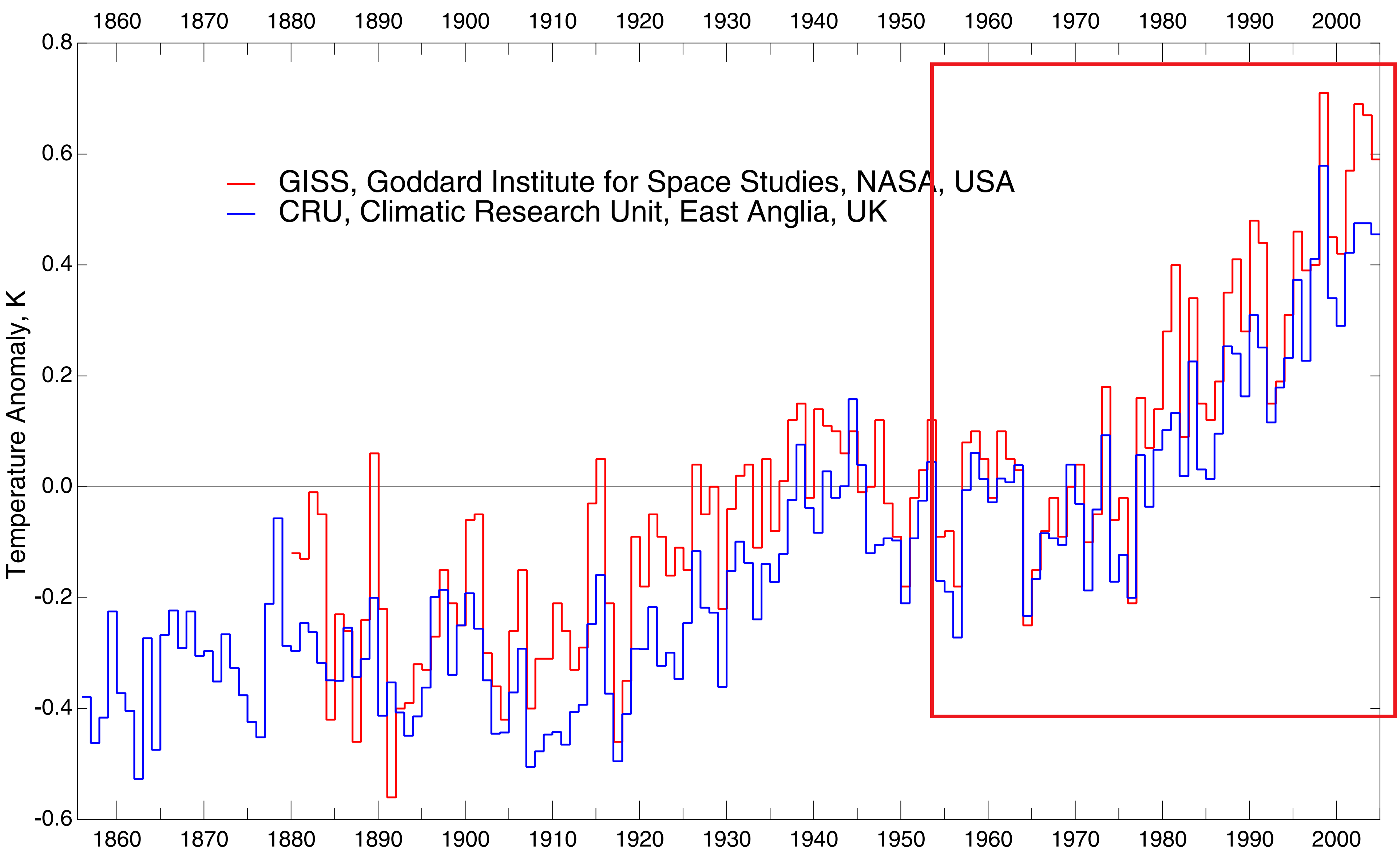
Levitus et al., 2005

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 OCEAN HEAT CAPACITY

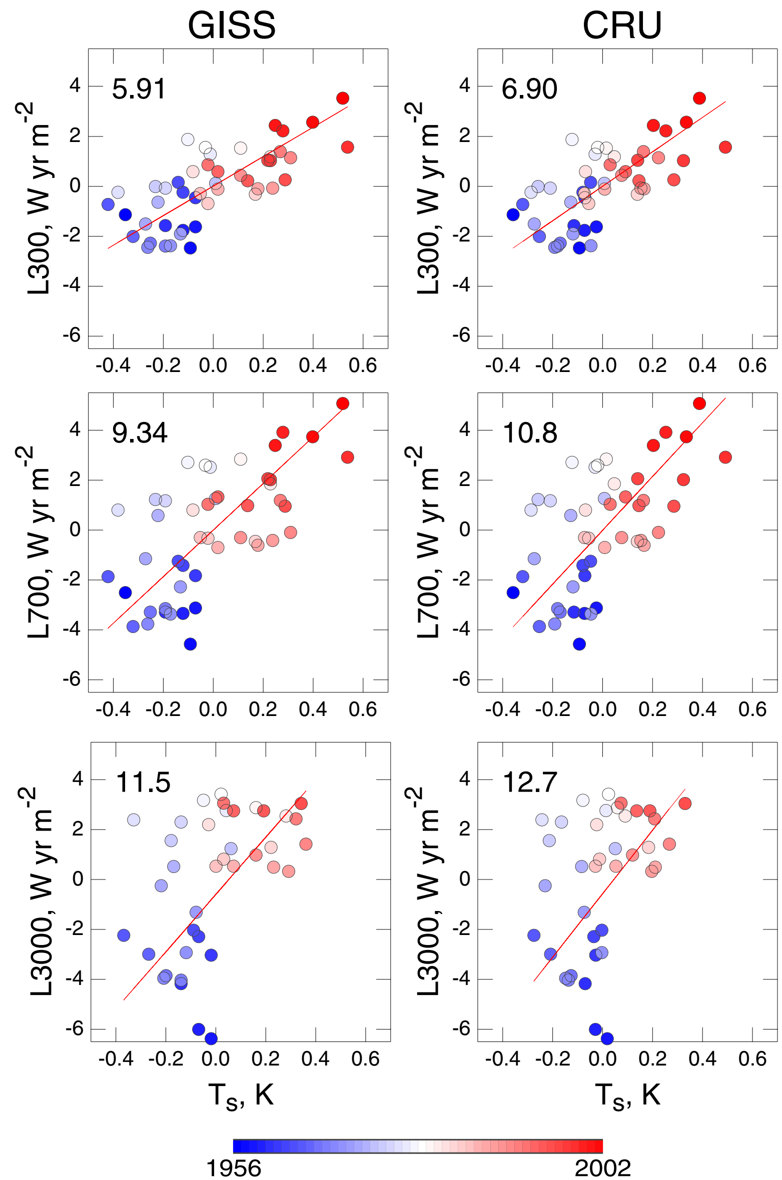
$$C = dH \,/\, dT_S$$

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:
12.1 ± 0.6 W yr m^{-2} K^{-1}
(equivalent to 91 m of ocean)



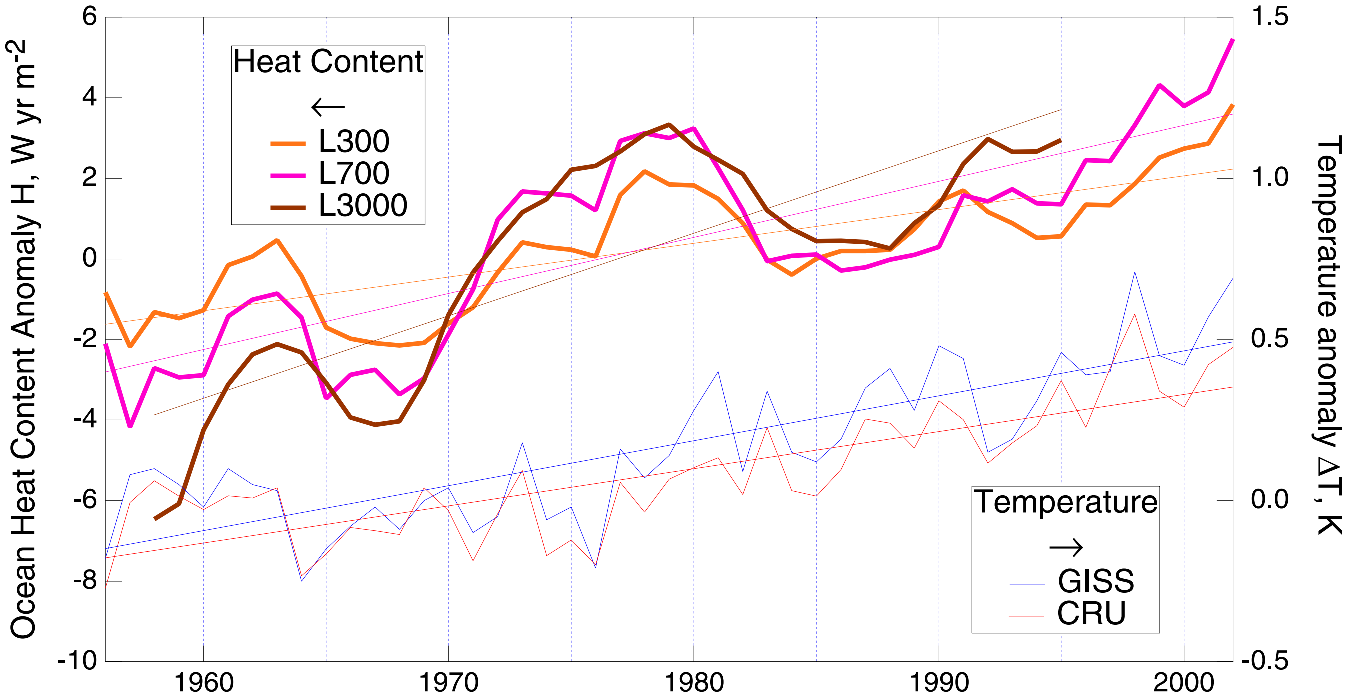
- ~53% of heat capacity is between surface and 300 m.

ALTERNATIVE 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.*, 2005



Depth	Effective global ocean heat capacity					
m	- - - - W yr m^{-2} K^{-1} - - - - -					
	GISS	CRU	Average	Uncertainty	Eq Depth, m	Fraction
300	6.0	7.3	6.6	0.6	50	0.17
700	10.0	12.0	11.0	1.0	83	0.12
3000	14.7	17.8	16.2	1.5	122	0.04

EFFECTIVE OCEAN HEAT CAPACITY

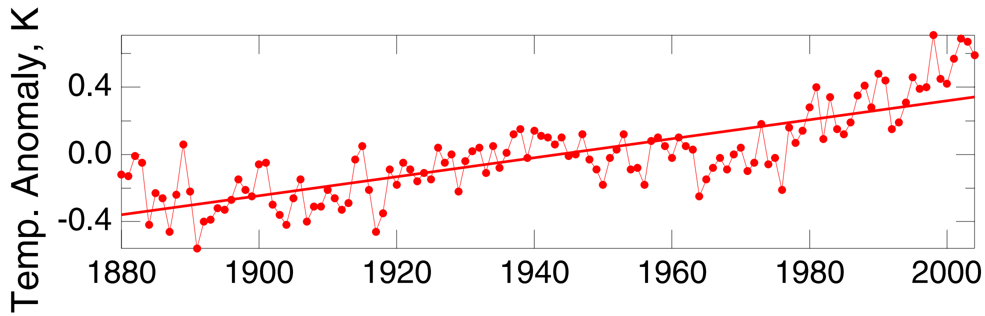
Ocean depth	Average, Methods 1 & 2	Uncertainty	Equivalent ocean depth
m	$W\ yr\ m^{-2}\ K^{-1}$		m
300	6.5	0.6	49
700	10.5	2.0	79
3000	14.2	3.0	107

- ~50% of heat capacity is between surface and 300 m.
- Other heat sinks raise global heat capacity to 17 ± 3.5 W yr m^{-2} K^{-1}.

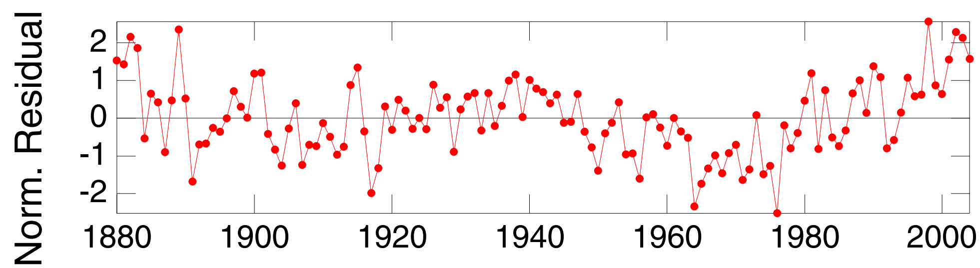
CHARACTERISTIC TIME OF EARTH'S CLIMATE SYSTEM FROM TIME SERIES ANALYSIS

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

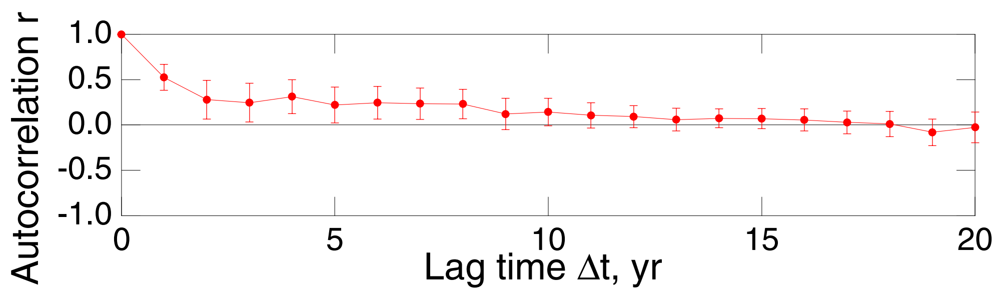
Recipe (GISS annual global mean surface temperature anomaly T_s)



1. Remove long term trend; plot the residuals:

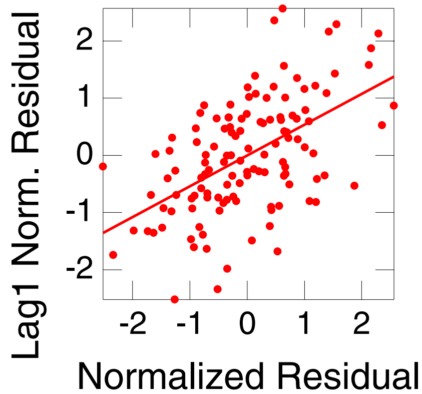


2. Calculate autocorrelogram (& standard deviations; Bartlett, 1948):

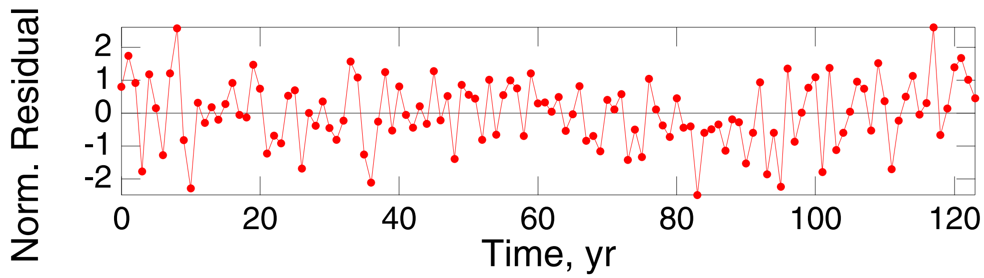


Recipe for determining climate system time constant, continued

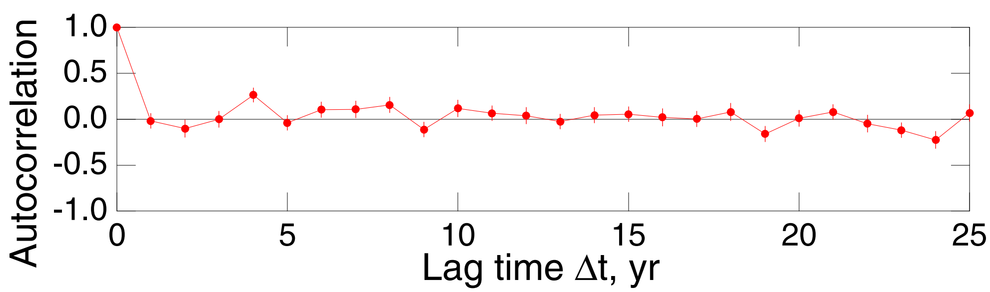
3. Examine the *lag*-1 autocorrelation:



4. Remove the trend; plot the residuals:



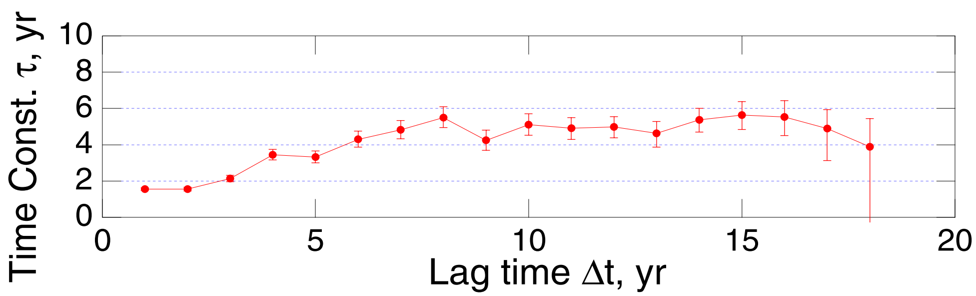
5. Examine for any remaining autocorrelation:



Recipe for determining climate system time constant, continued

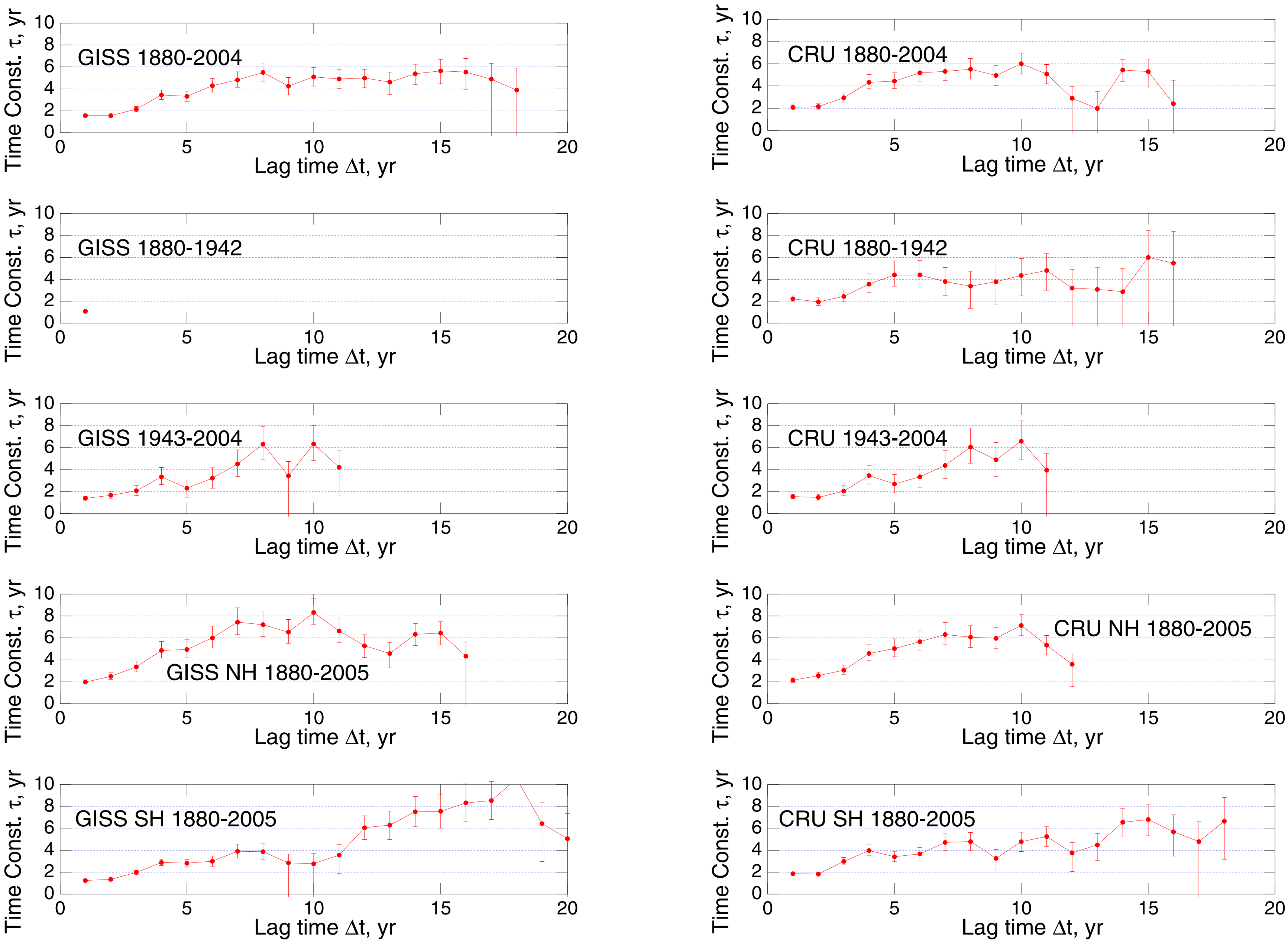
6. If no residual autocorrelation (Markov process) calculate time constant τ for relaxation of system to perturbation:

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

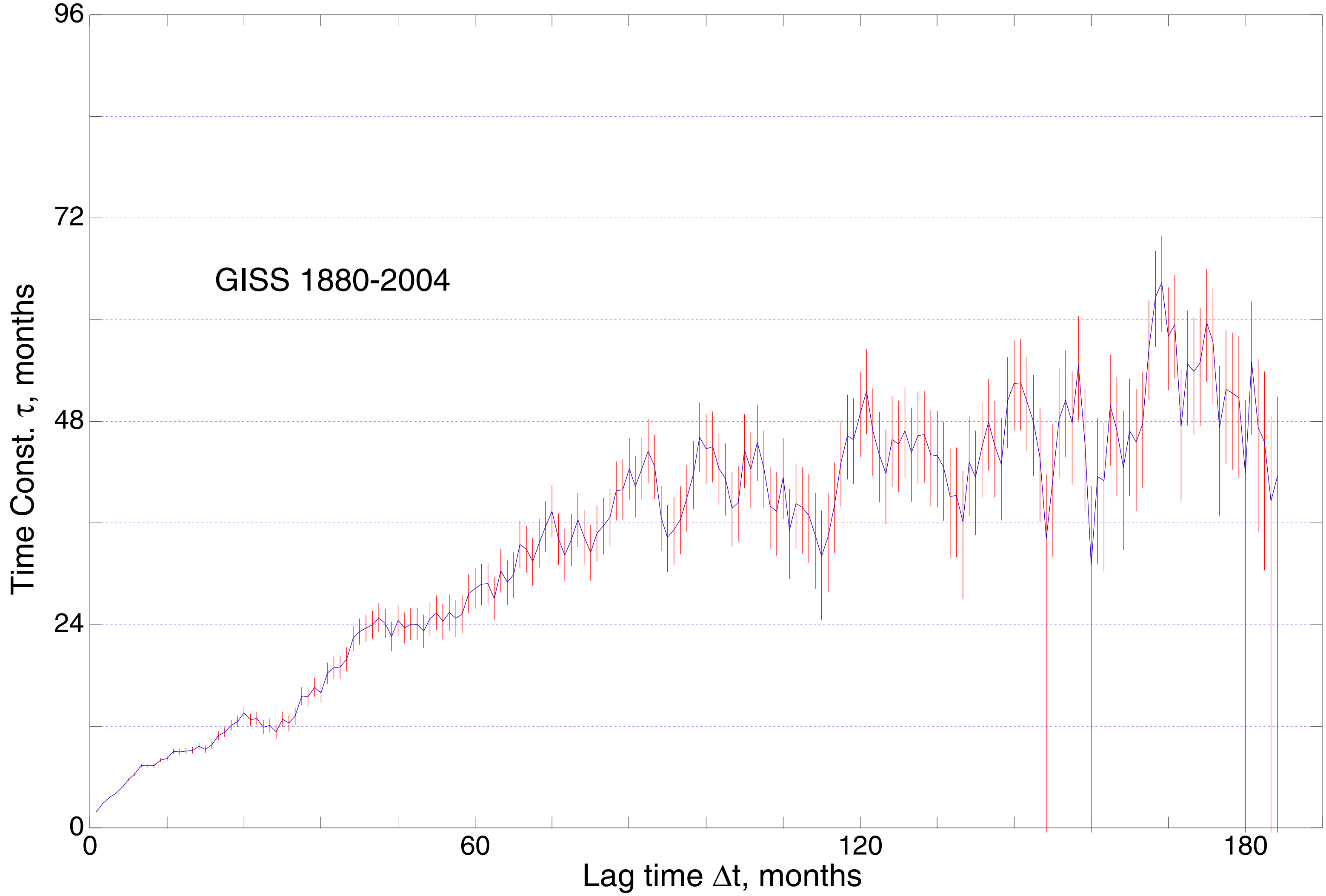


- Time constant τ ***increases with increasing lag time***.
- Implies coupling of T_s to a system of longer time constant.
- On decadal scale time constant asymptotes to 5 ± 1 yr.
- This is the ***e-folding time constant*** for relaxation of global mean surface temperature to perturbations on the decadal scale.

THIS RESULT IS ROBUST



SAME RESULT WITH DESEASONALIZED MONTHLY DATA

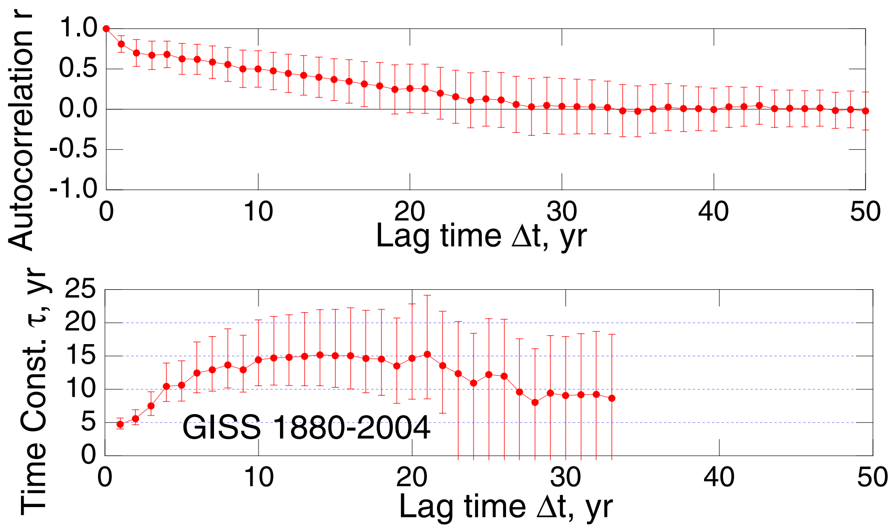


- Again the time constant is about 5 yr.

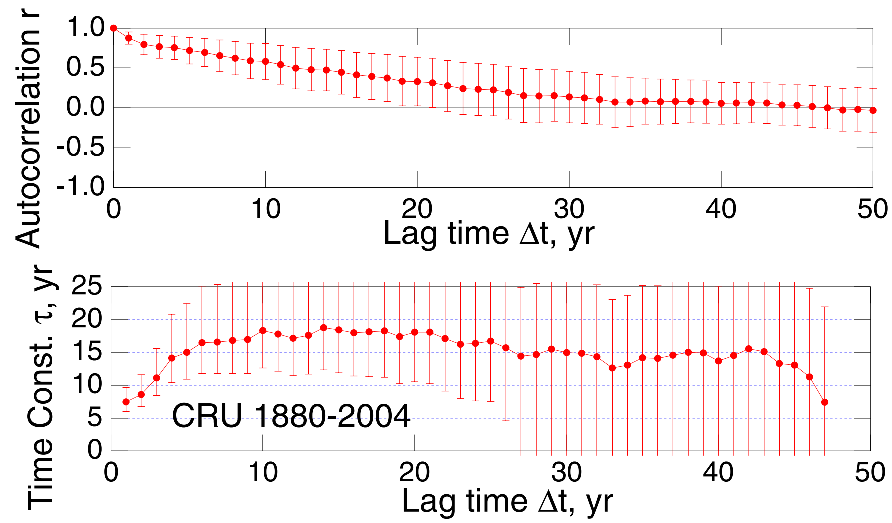
ALTERNATIVE APPROACH TO DETERMINATION OF TIME CONSTANT

Use non-detrended time series data

GISS data



CRU data



- The time constant is about 16 yr.
- The result depends strongly on the approach to time series analysis.

SUMMARY RESULTS

Quantity	Unit	***Detrended*** time series	***Non-detr*** time series
Effective global heat capacity C	W yr m^{-2} K^{-1}	16.9	16.9
Effective climate system time constant τ	yr	5	16
Equilibrium climate sensitivity $\lambda^{-1} = \tau / C$	K/(W m^{-2})	0.30	0.96
Equilibrium temperature increase for doubled CO_2, $\Delta T_{2\times}$	K	1.1	3.6
Total forcing over the 20th century, $F_{20} = \Delta T_{20} / \lambda^{-1}$	W m^{-2}	1.9	0.59
Forcing in 20th century other than GHG forcing, $F_{20}^{nghg} = F_{20} - F_{20}^{ghg}$	W m^{-2}	-0.3	-1.6

SUMMARY RESULTS *cont'd*

Quantity	Unit	***Detrended*** time series	***Non-detr*** time series
Lag in temperature change, ΔT_{lag}	K	0.03	0.09
Temperature increase in 20th century due to GHG forcing	K	0.66	2.1
Temperature increase in 20th century due to CO_2 forcing	K	0.37	1.2
Temperature decrease in 20th century due to other forcing	K	-0.09	-1.5
Temperature increase 1750-1998 due to greenhouse gas forcing	K	0.72	2.30

SUMMARY

- The ***effective heat capacity*** of Earth's climate system is 17 ± 3.5 W yr m^{-2} K^{-1} ≈ 180 m of the world ocean.
- The ***time constant*** of Earth's climate system is 5 ± 1 years OR 16 ± 3 years.
- ***This needs to be resolved***.
- Climate system response to greenhouse forcing is in ***near steady state***, with little further warming (due to present GH gases) "in the pipeline."

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.