CONSIDER A SPHERICAL EARTH

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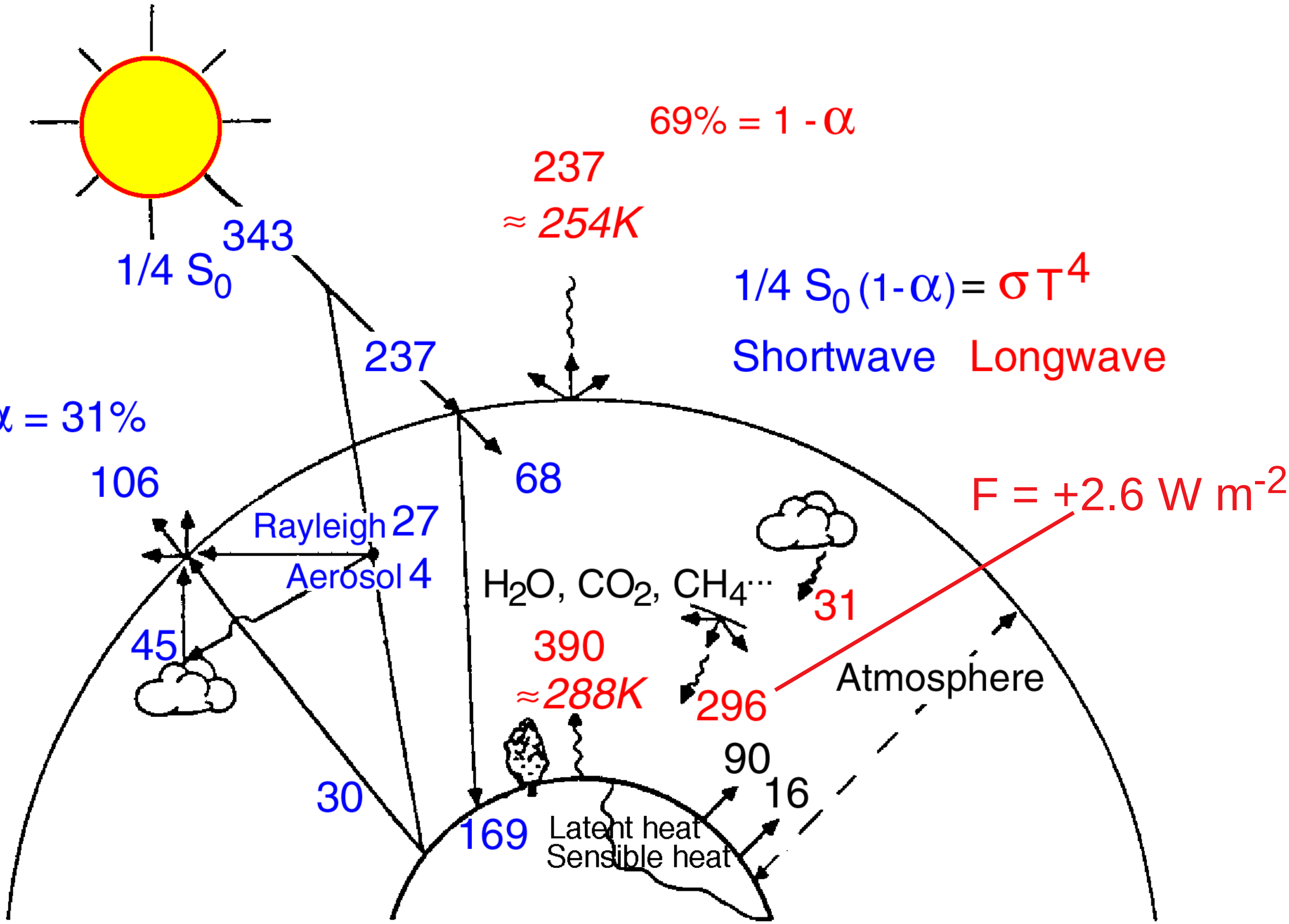
http://www.ecd.bnl.gov/steve

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

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.

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

CLIMATE SENSITIVITY

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

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

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

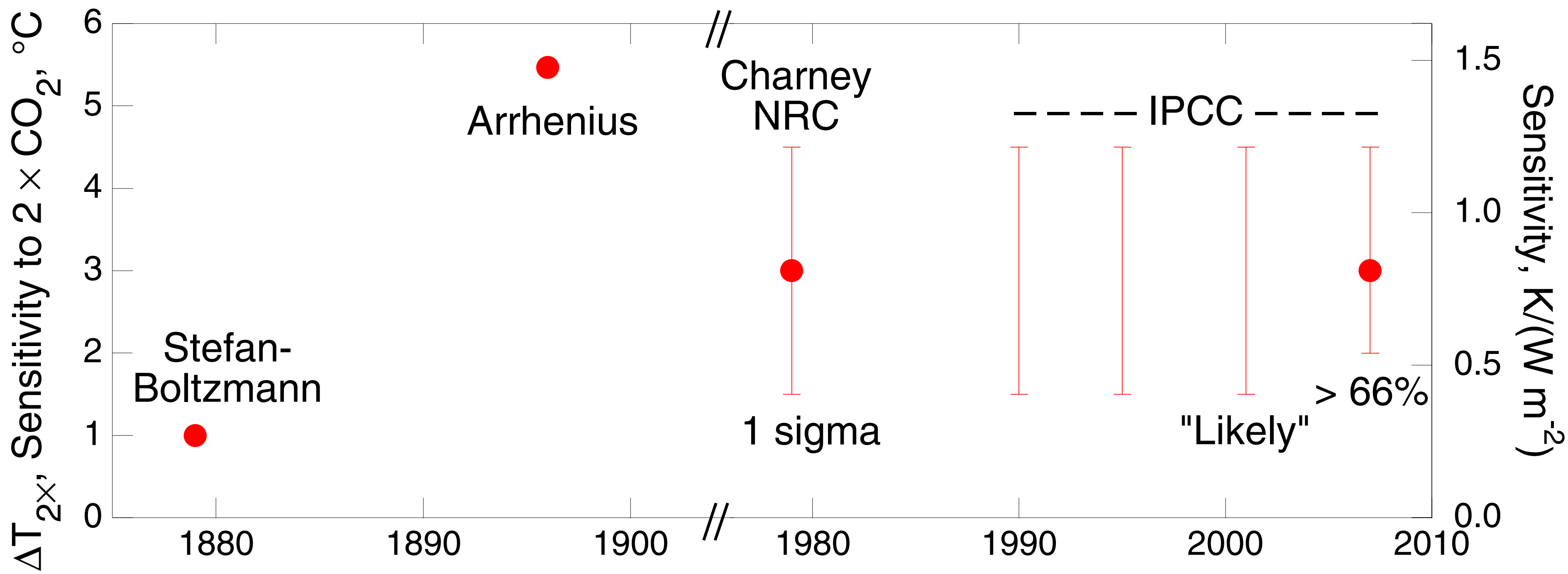
Climate sensitivity is often expressed as the temperature for doubled CO_2 concentration $\Delta T_{2\times}$.

$$\Delta T_{2\times} = \lambda^{-1} \Delta F_{2\times}$$

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

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

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

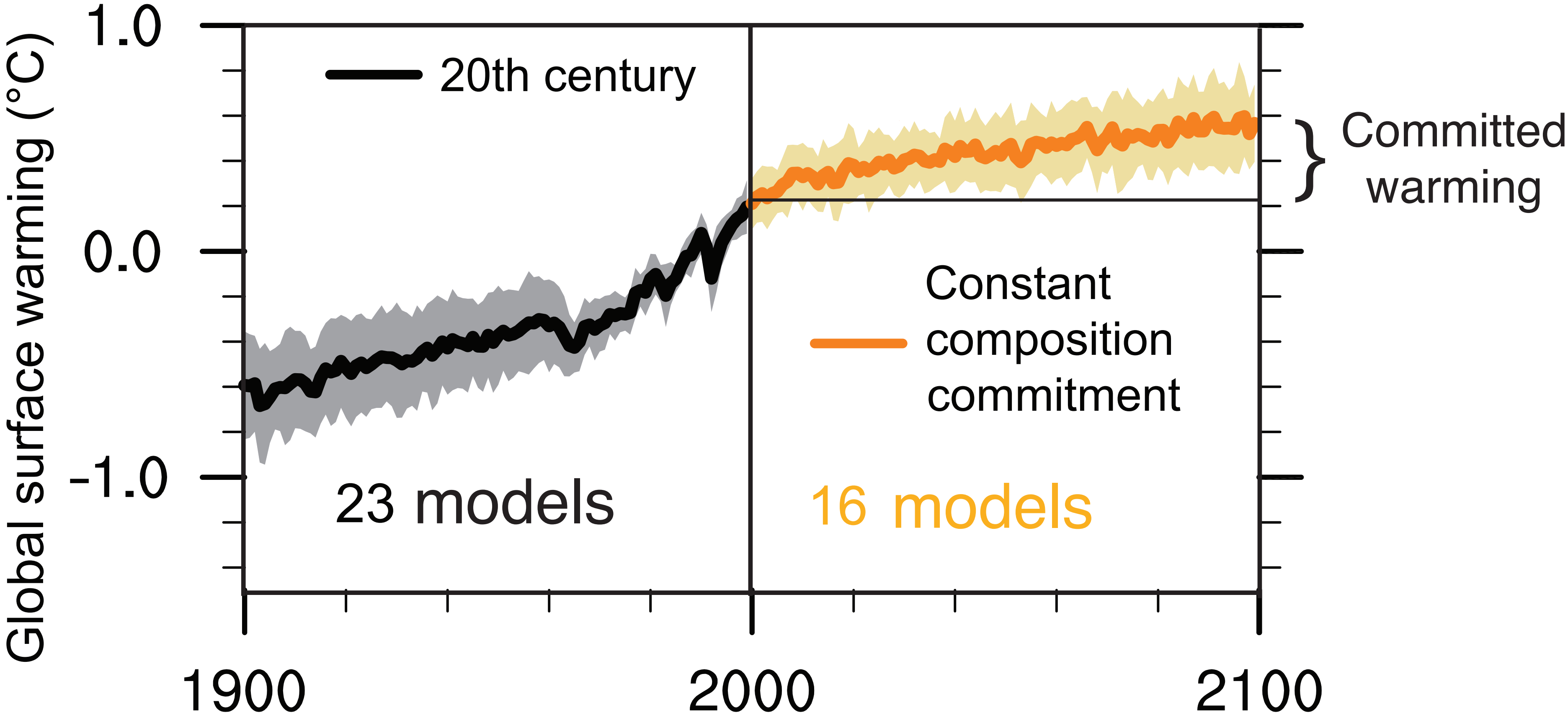


Despite extensive research, climate sensitivity remains ***highly uncertain***.

More on this in tomorrow’s lecture.

COMMITTED WARMING IN CLIMATE MODEL RUNS

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



Temperature continues to increase for composition held constant.

Projected incremental 21st century is 50% beyond warming already realized.

"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

WHAT CAN WE LEARN FROM ENERGY BALANCE MODELS?

EMPIRICAL DETERMINATION OF EARTH'S CLIMATE SENSITIVITY

JUST PUBLISHED IN JGR

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D24S05, doi:10.1029/2007JD008746, 2007

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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}.

STOVE-TOP MODEL OF EARTH'S CLIMATE SYSTEM

STOVE-TOP MODEL OF EARTH'S CLIMATE SYSTEM

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

H = heat content $\quad T$ = temperature

C = system heat capacity

Q = heating rate from stove

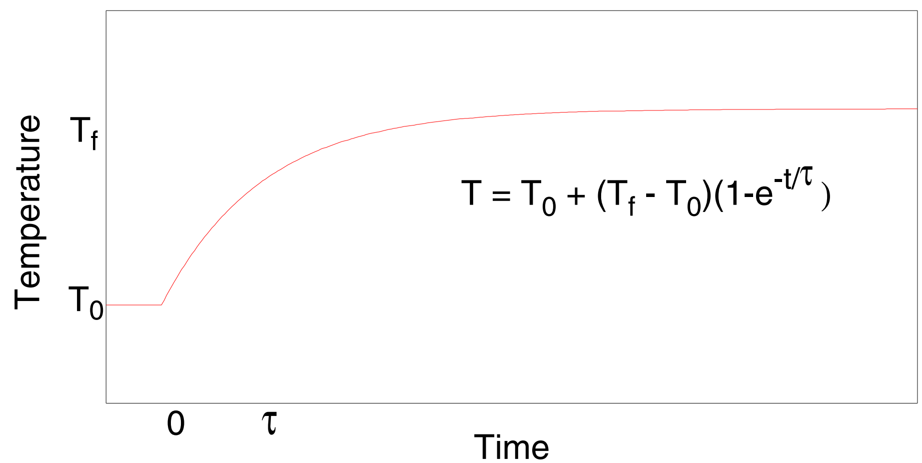
T_{amb} = ambient temperature

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

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

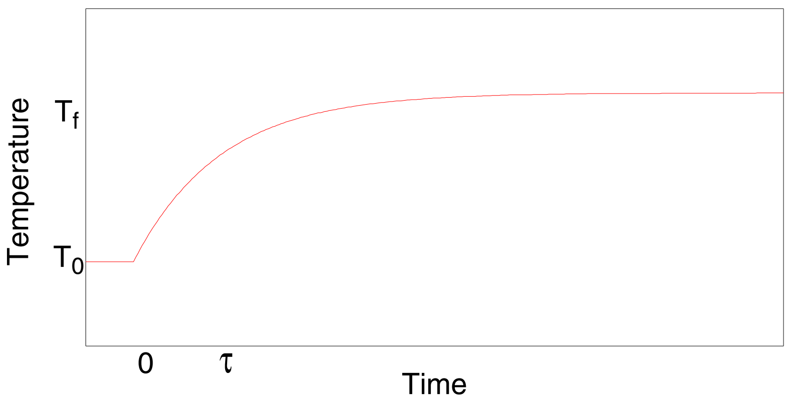
Sensitivity: $\lambda^{-1} \equiv \dfrac{\Delta T_\infty}{F} = \dfrac{1}{k}$

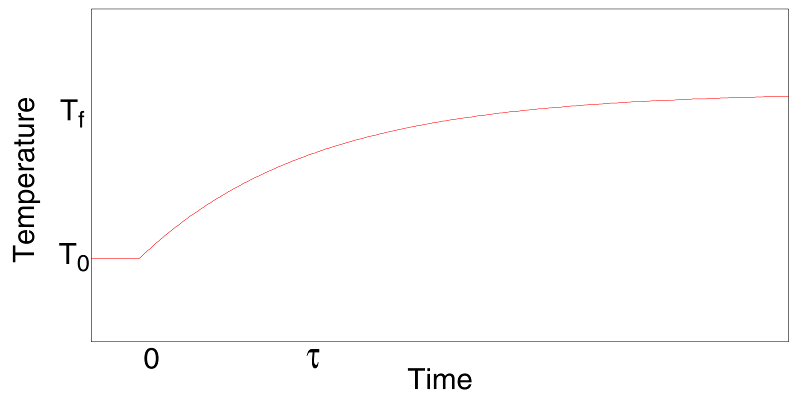
Time constant: $\tau = C\lambda^{-1}$



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 $\boxed{\lambda^{-1} = \tau / C.}$

BILLIARD BALL MODEL OF EARTH'S CLIMATE SYSTEM

BILLIARD BALL TEMPERATURE SENSITIVITY AND TIME CONSTANT

Evaluated according to the Stefan-Boltzmann radiation law

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

Initially $Q_0 = \sigma T_0^4$

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

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

Relaxation time constant is $\tau_{\text{S-B}} = \dfrac{T_0 C}{4Q_0} = C\lambda_{\text{S-B},0}^{-1}$ or $\lambda_{\text{S-B},0}^{-1} = \dfrac{\tau_{\text{S-B}}}{C}$

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 × 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: $C\dfrac{dT_s}{dt} = \dfrac{dH}{dt} = Q - E = \gamma J - \varepsilon\sigma T_s^4$

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

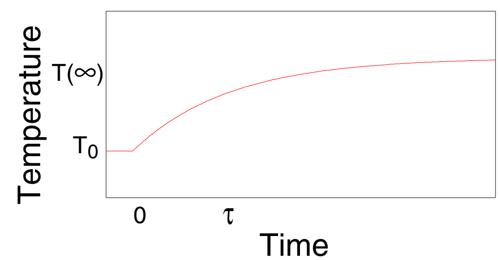
σ is Stefan-Boltzmann constant

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

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

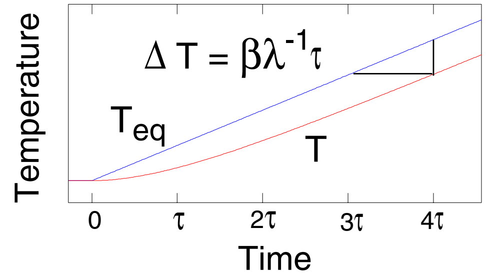
τ is climate system time constant $\tau = C\lambda^{-1}$ or $\boxed{\lambda^{-1} = \tau / C}$

One equation in three unknowns

TEMPERATURE RESPONSE TO LINEARLY INCREASING FORCING

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

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

APPROACH

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

Evaluate sensitivity as $\lambda^{-1} = \tau/C$.

DETERMINING EARTH’S HEAT CAPACITY BY OCEAN CALORIMETRY

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

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

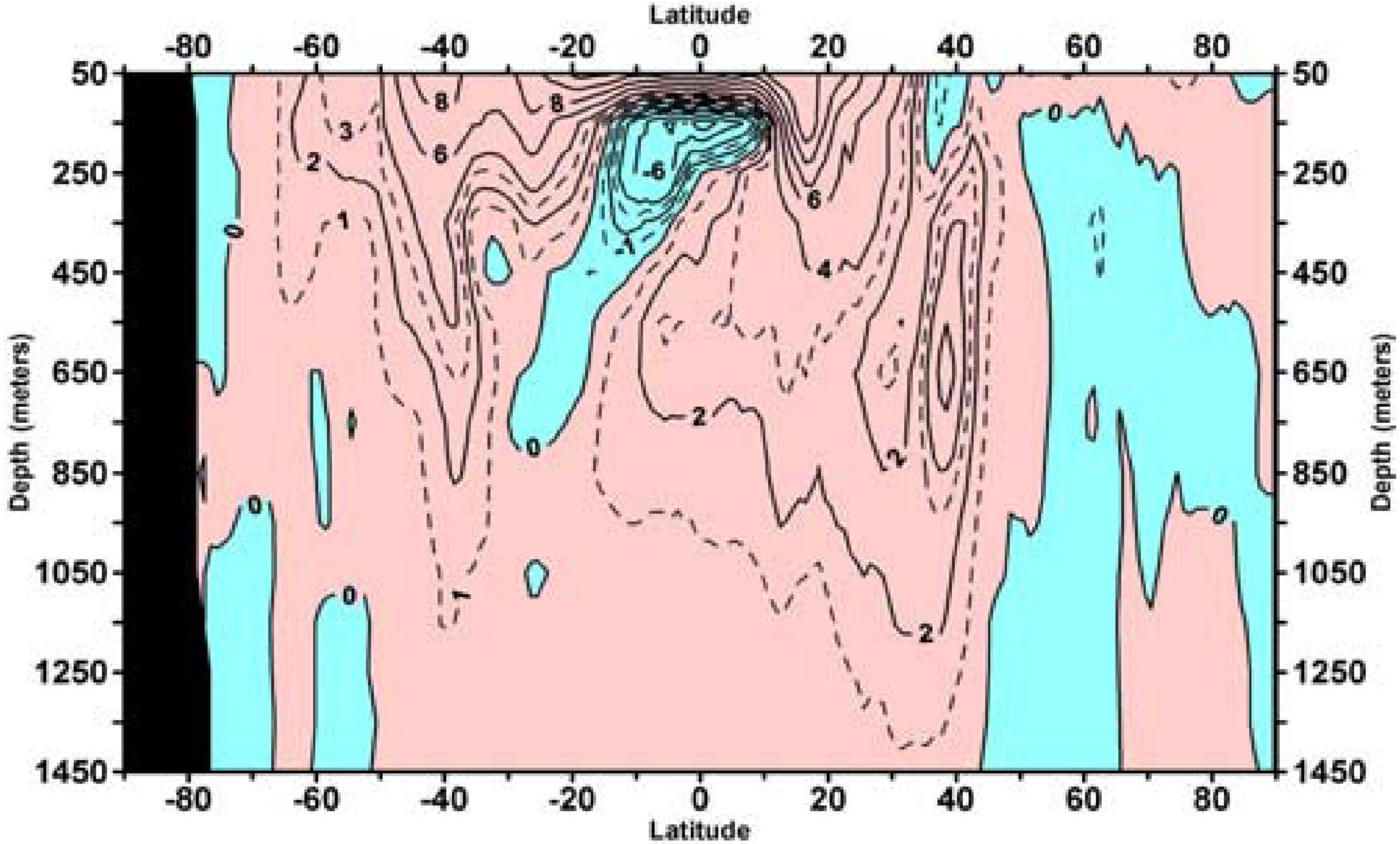
C: Global heat capacity

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}



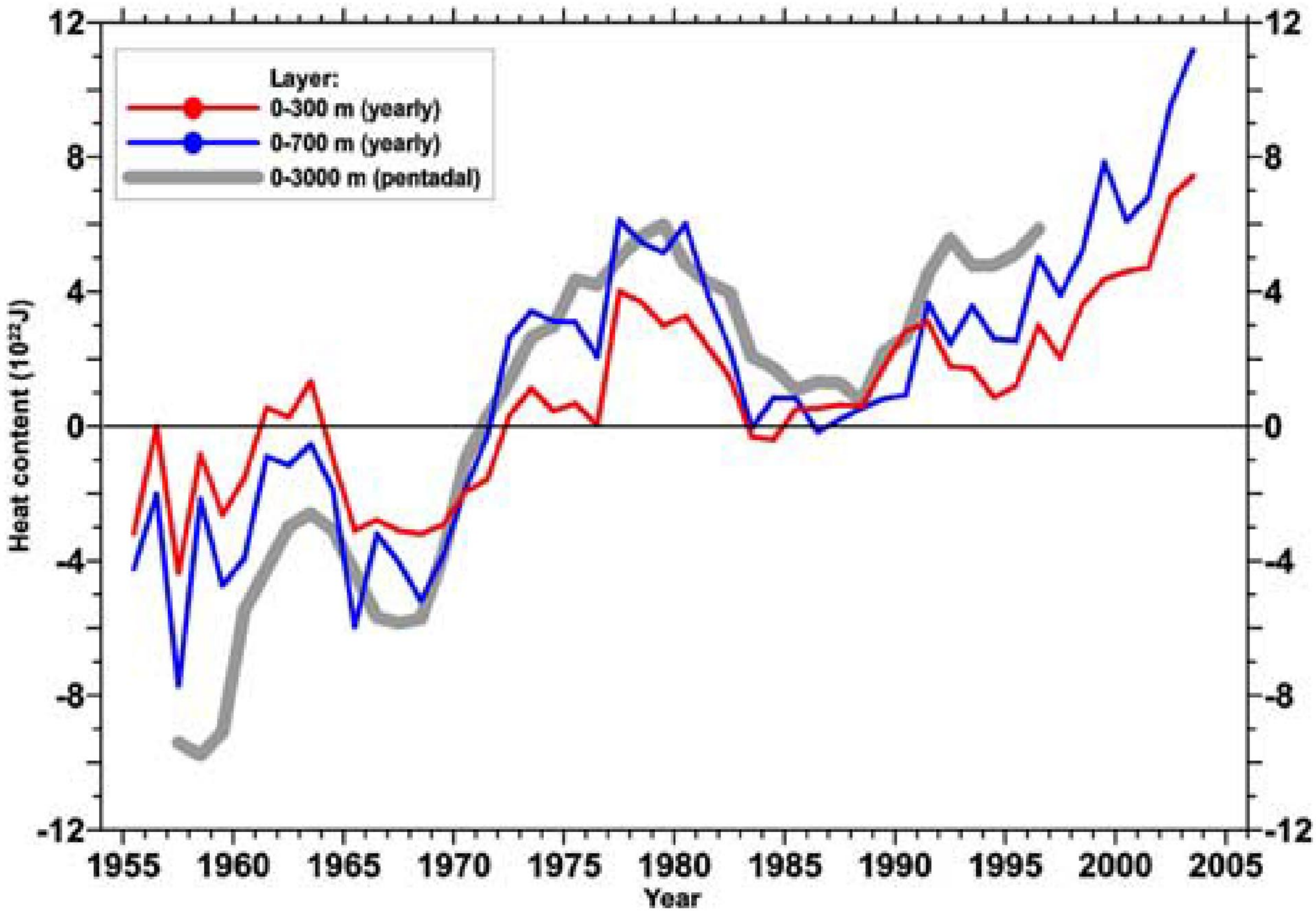
- Heating is greatest in upper ocean, with downwelling plumes.

Warming of the world ocean, 1955–2003

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

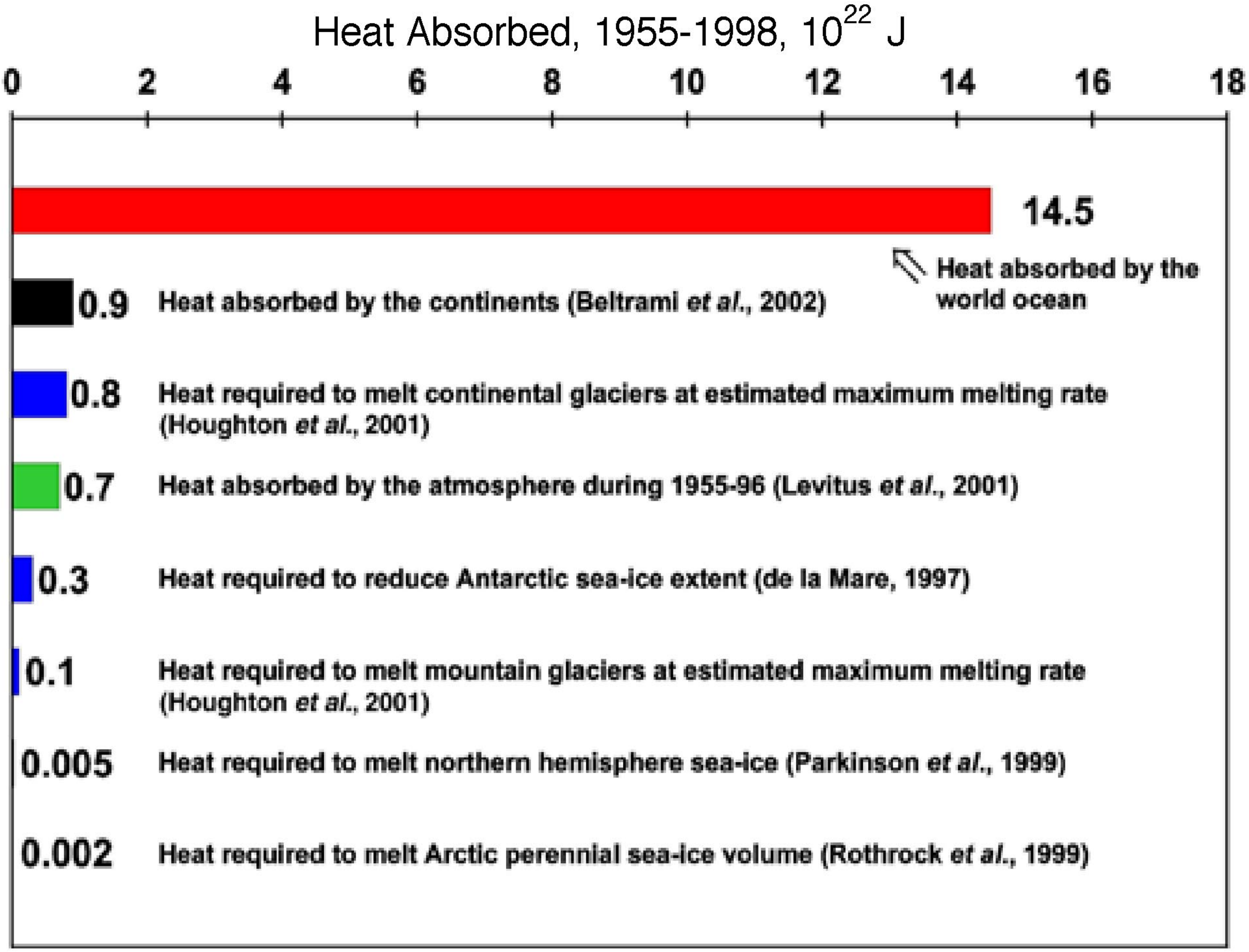
GEOPHYSICAL RESEARCH LETTERS, VOL. 32, 2005

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



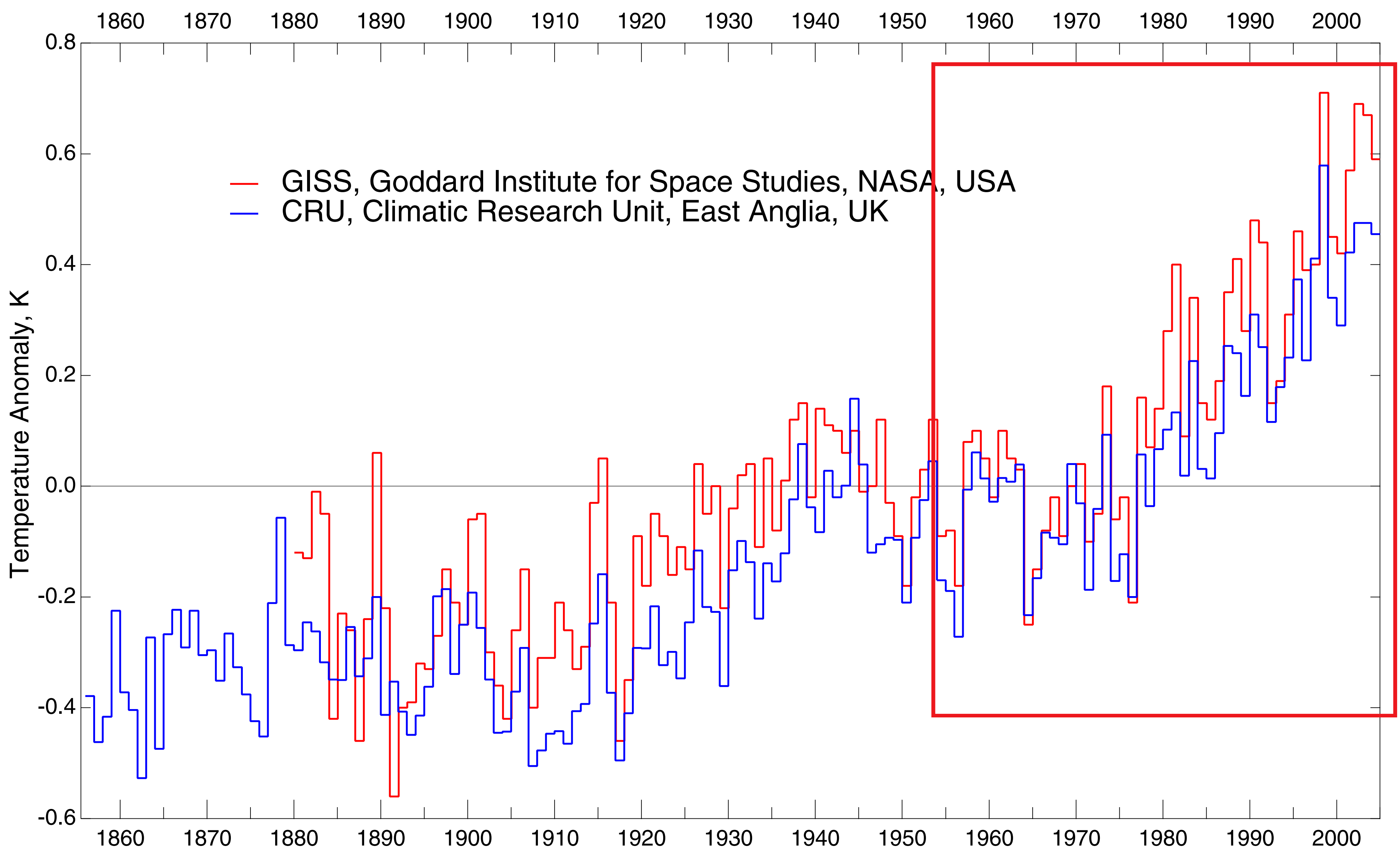
Levitus et al., 2005

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

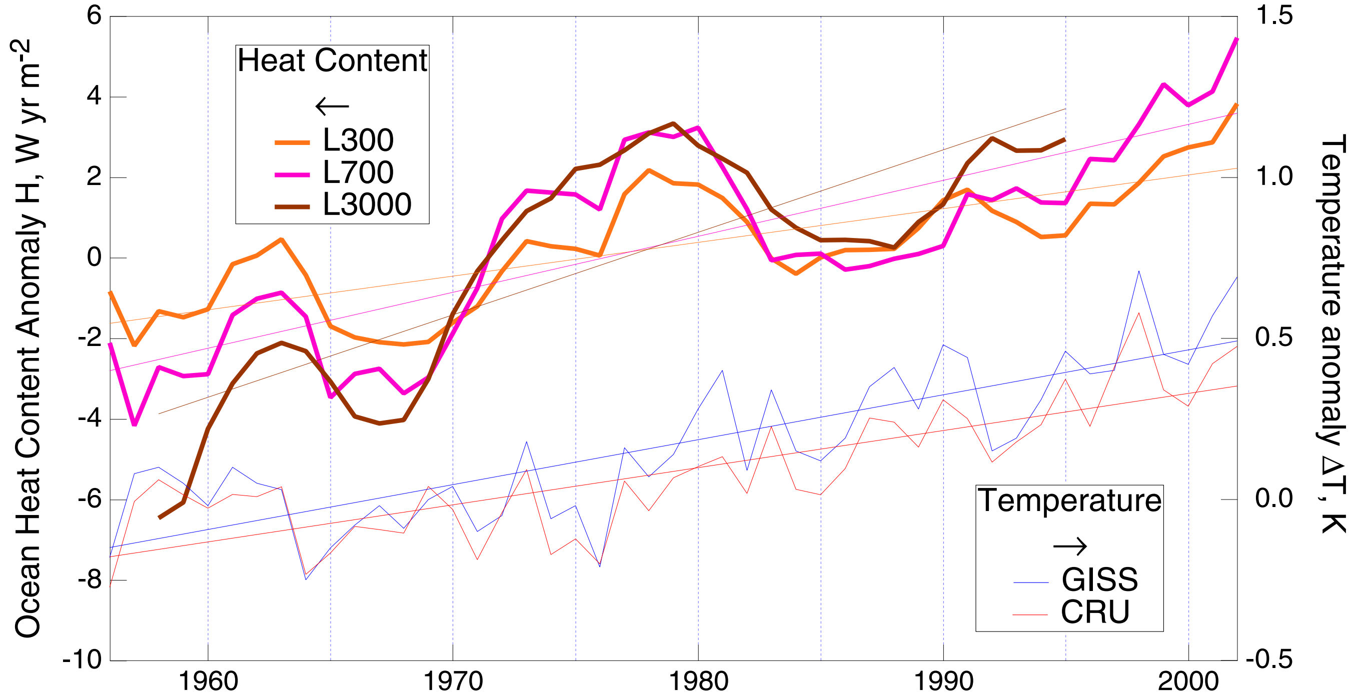


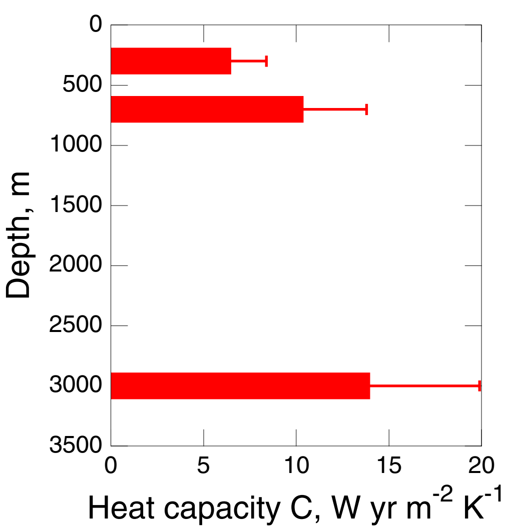
EMPIRICAL DETERMINATION OF OCEAN HEAT CAPACITY

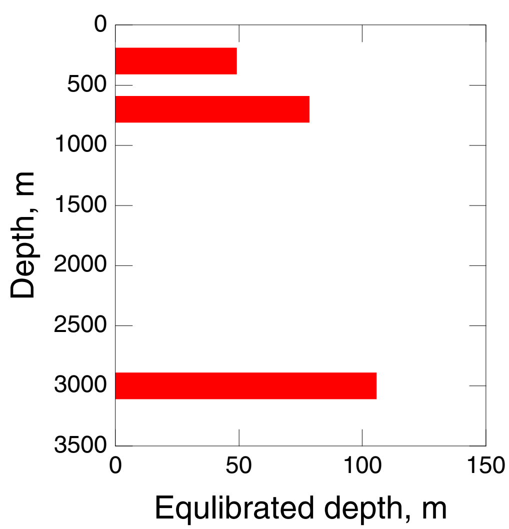
$$C = \frac{dH/dt}{dT_s/dt}$$

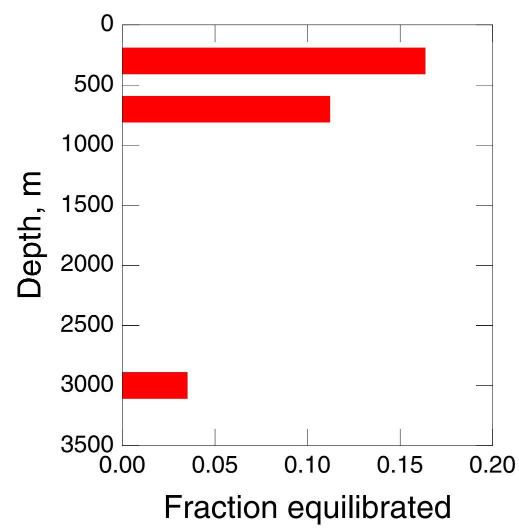
Surface temperature T_s: GISS, CRU

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







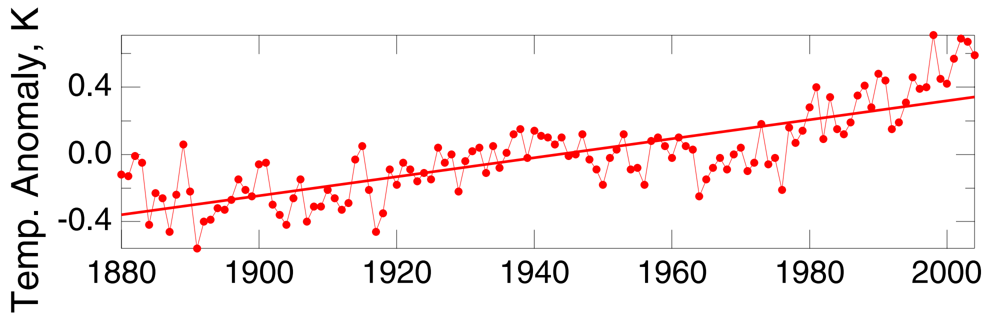


- ~50% of heat capacity is between surface and 300 m.
- Other heat sinks raise global heat capacity to 17 ± 7 W yr m^{-2} K^{-1}.

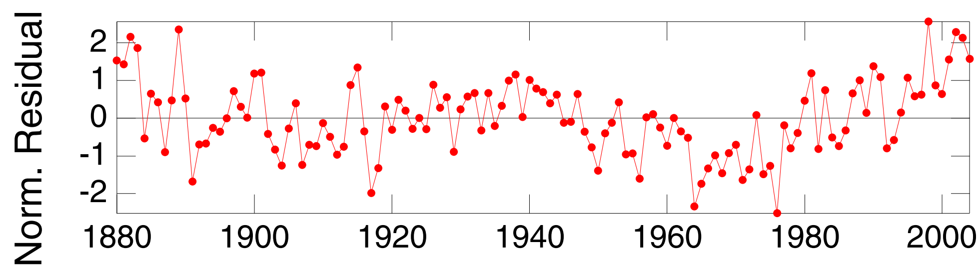
CHARACTERISTIC TIME OF EARTH’S CLIMATE SYSTEM FROM TIME SERIES ANALYSIS

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

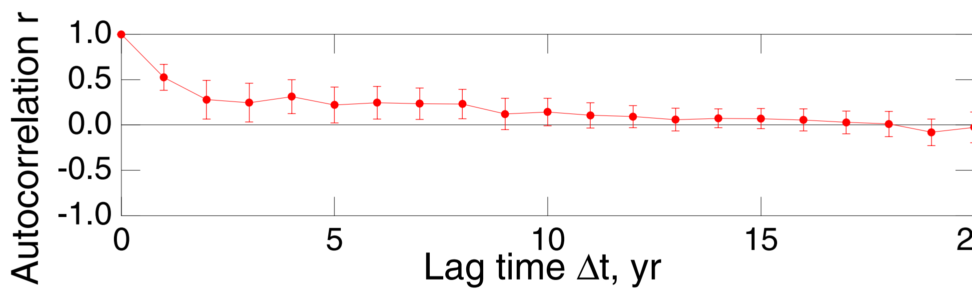
Recipe (GISS annual global mean surface temperature anomaly T_s)



1. Remove long term trend; plot the residuals:

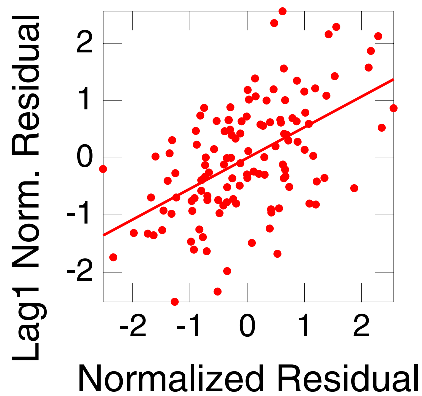


2. Calculate autocorrelogram (& standard deviations; Bartlett, 1948):

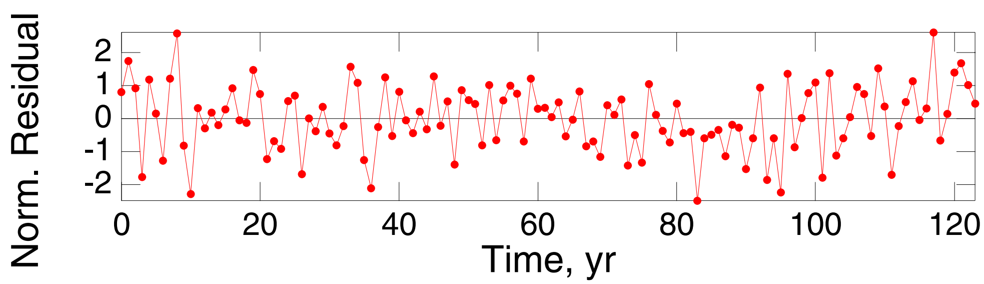


Recipe for determining climate system time constant, continued

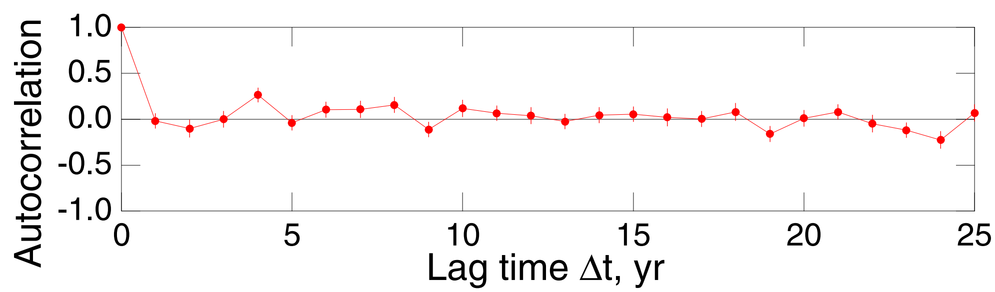
3. Examine the *lag*-1 autocorrelation:



4. Remove the trend; plot the residuals:



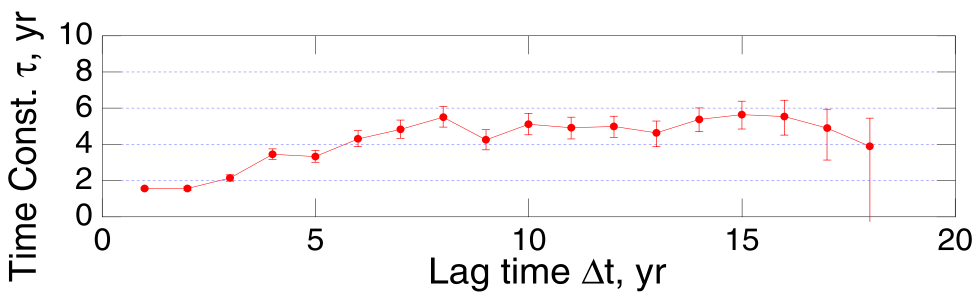
5. Examine for any remaining autocorrelation:



Recipe for determining climate system time constant, continued

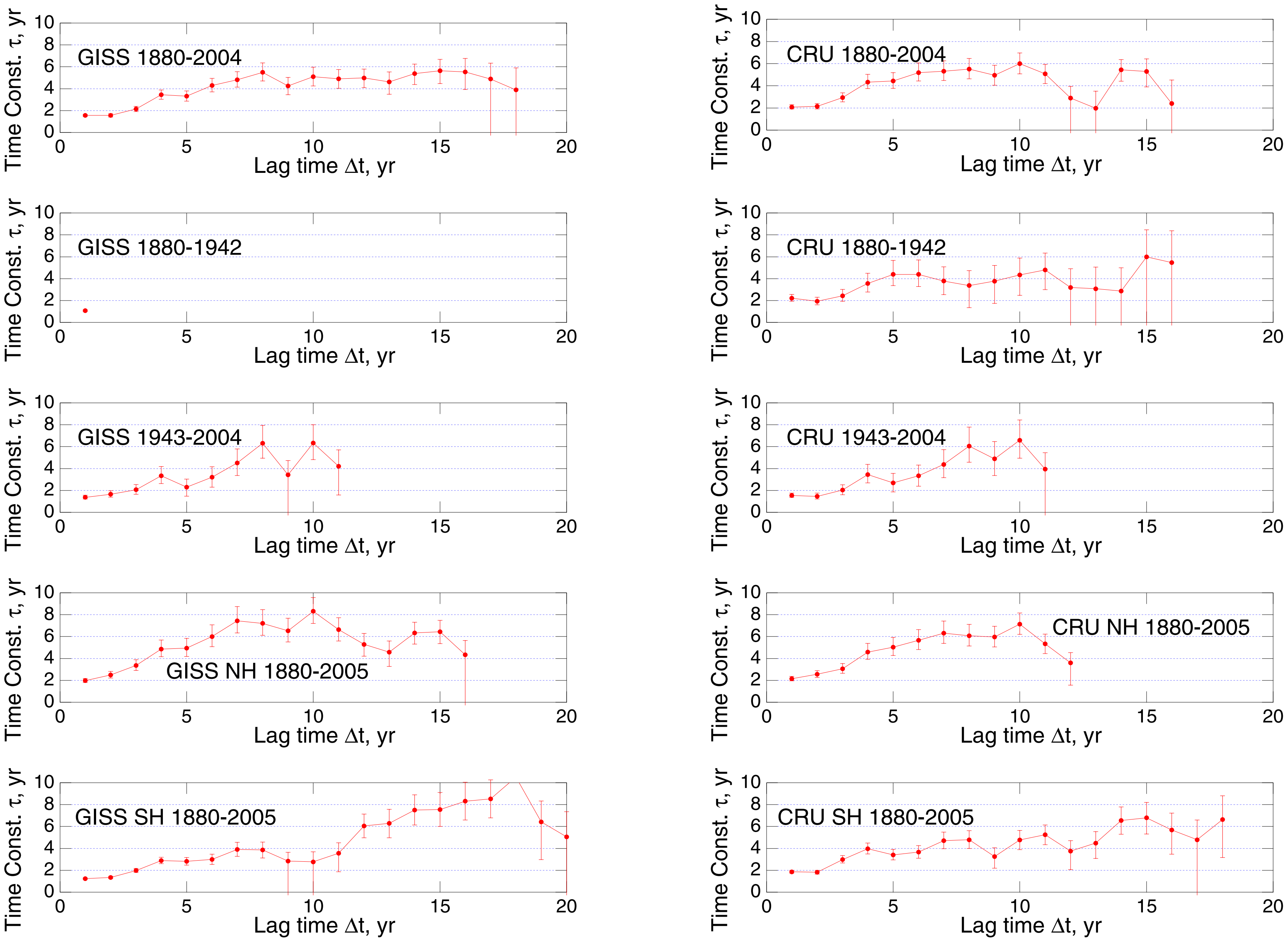
6. If no residual autocorrelation (Markov process) calculate time constant τ for relaxation of system to perturbation:

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



- 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 $\boxed{5 \pm 1 \text{ yr.}}$
- This is the ***e-folding time constant*** for relaxation of global mean surface temperature to perturbations on the decadal scale.

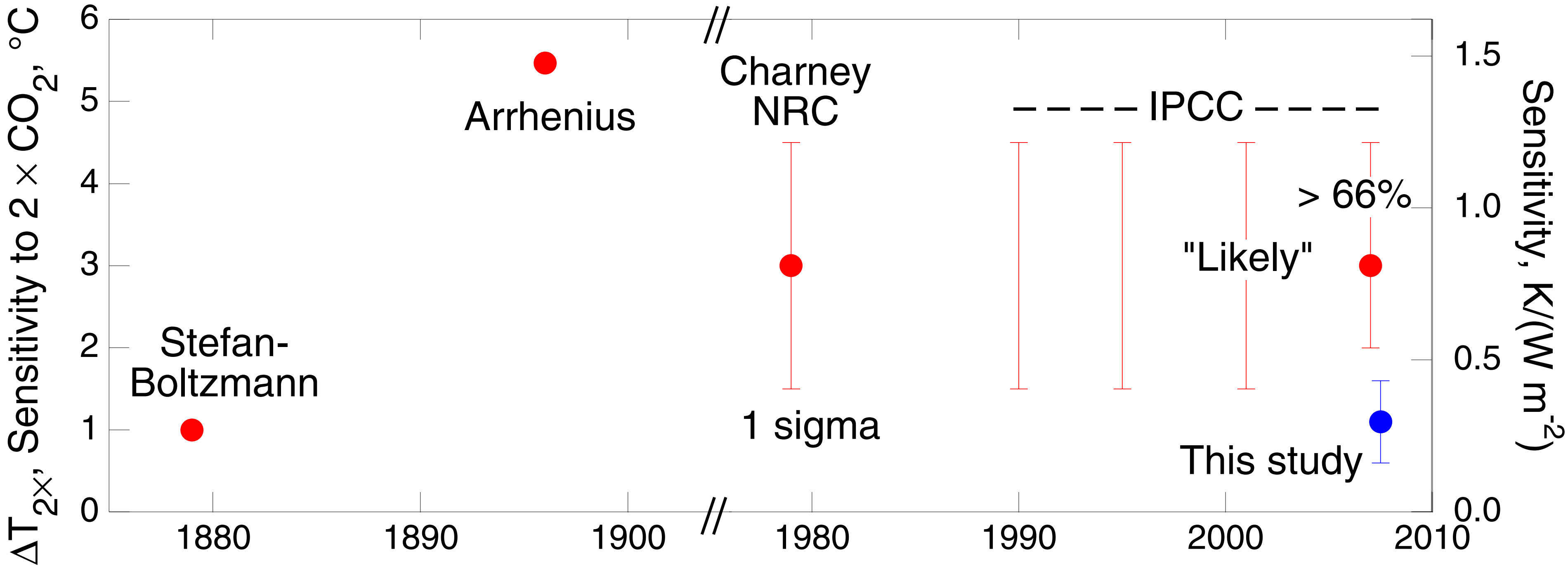
THIS RESULT IS ROBUST



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 $\lambda^{-1} = \tau / C$	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, $F_{20} = \Delta T_{20} / \lambda^{-1}$	W m^{-2}	**1.9**	**0.9**
Forcing in 20th century other than GHGs (*mainly aerosols*), $F_{20}^{\text{other}} = F_{20} - F_{20}^{\text{ghg}}$	W m^{-2}	**-0.3**	**1.0**
Lag in temperature change, ΔT_{lag}	K	**0.03**	

COMPARISON WITH PREVIOUS RESULTS



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

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.

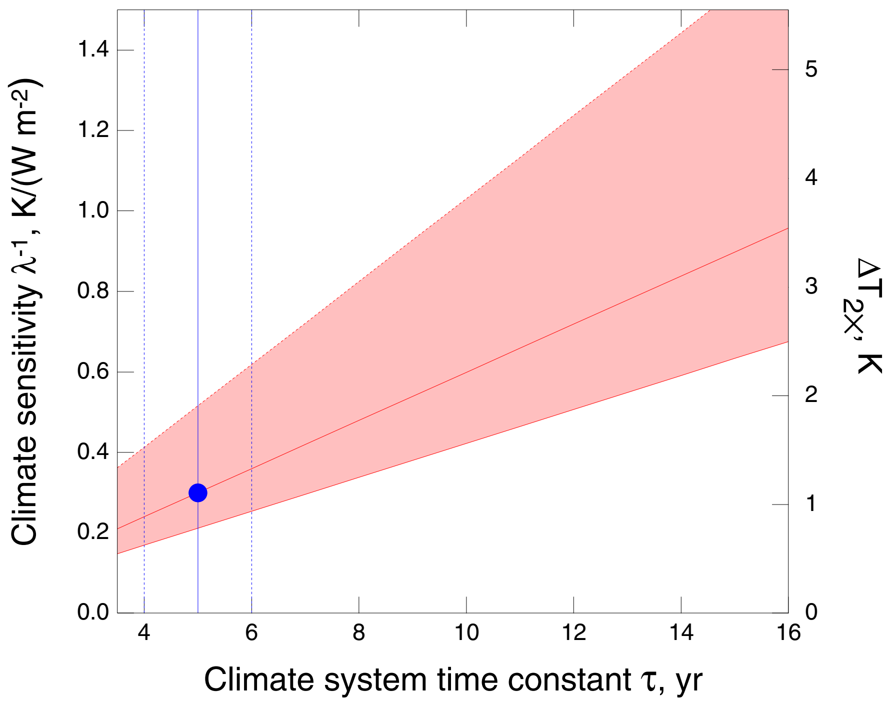
- Earth's climate system is much more complex than can be represented by a single-compartment model.

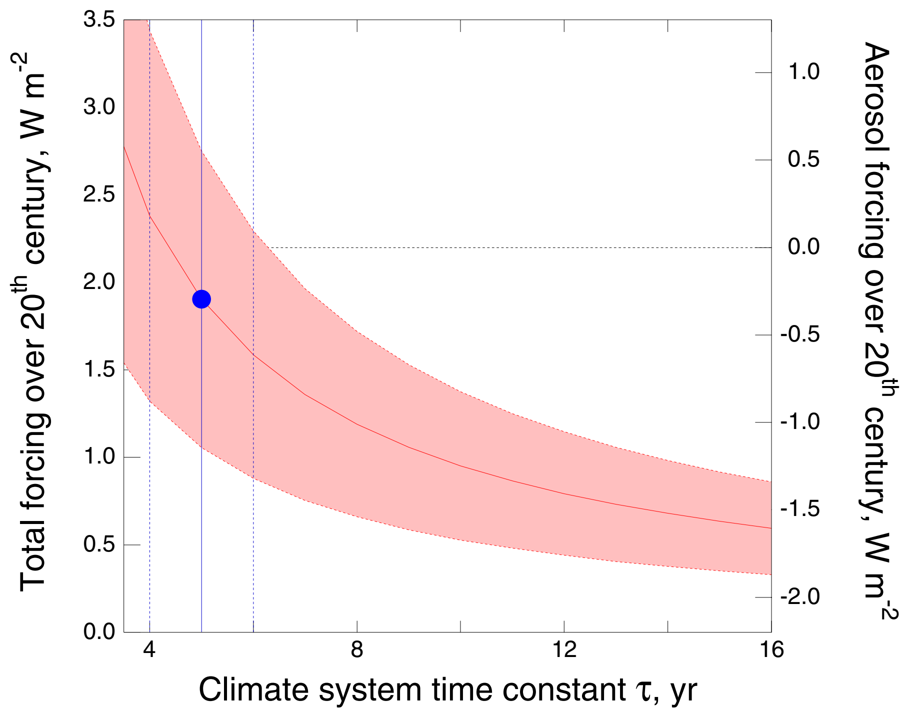
  Multiple time constants, multiple heat capacities.

CLIMATE SENSITIVITY AND INFERRED 20th CENTURY TOTAL AND AEROSOL FORCING

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

$$\lambda^{-1} = \tau / C \qquad F_{20} = \Delta T_{20} / \lambda^{-1} = C\Delta T_{20} / \tau \qquad F_{\mathrm{aer}} = F_{20} - F_{\mathrm{GHG}}$$





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.

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 ***effective heat capacity*** of Earth's climate system is 17 ± 7 W yr m^{-2} K^{-1} $\approx$ 150 m of the world ocean.

  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 ***equilibrium sensitivity*** of Earth's climate system is 0.30 ± 0.14 K / (W m^{-2}); $\Delta T_{2\times} = 1.1 \pm 0.5$ K.

CONCLUDING OBSERVATION

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