

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

Stephen E. Schwartz



Upton, New York, USA

Workshop on Past, Present and Future Climate Dynamics,
Feedback Mechanisms, and Land – Atmosphere Interactions

the FINNISH CULTURAL FOUNDATION



Vuosaari (Helsinki) Finland
22-23 October 2007

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

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),

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

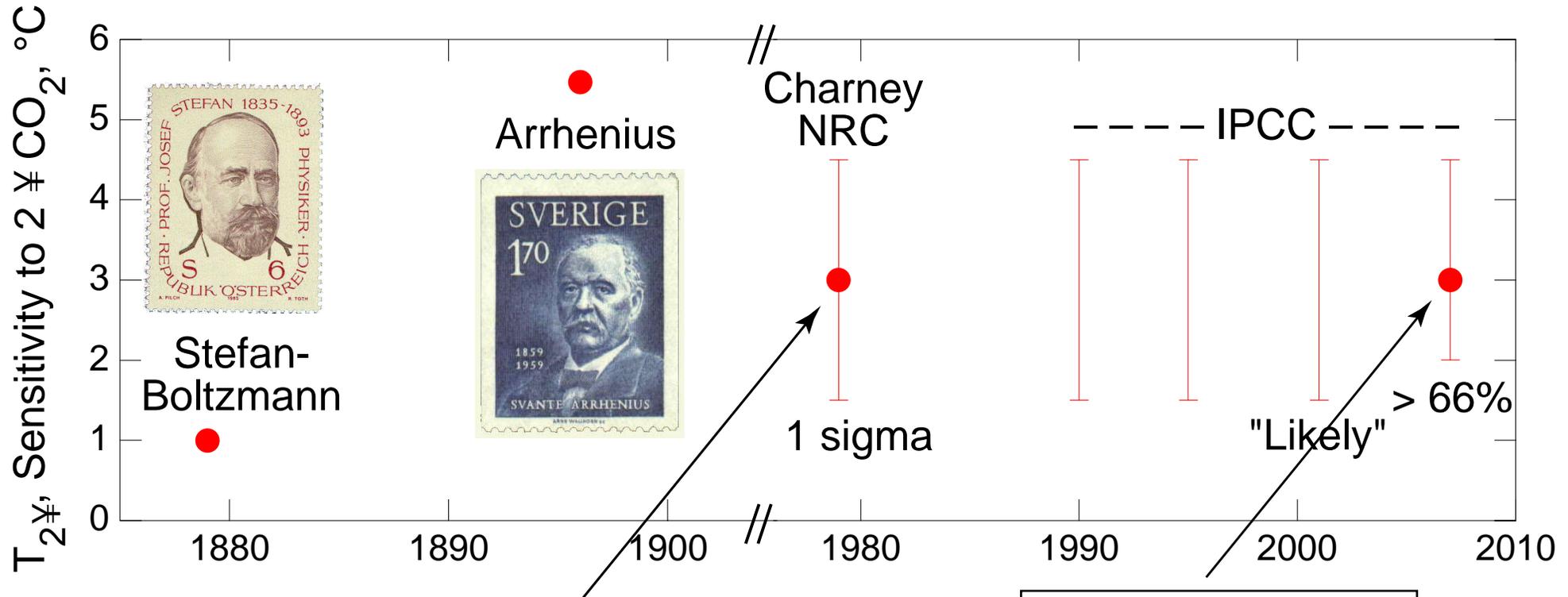
Climate sensitivity is not known and is the objective of much current research on climate change.

Climate sensitivity is often expressed as the temperature for doubled CO₂ concentration $\Delta T_{2\times}$.

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

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

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



**Carbon Dioxide and Climate:
A Scientific Assessment**
NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979



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 CO₂* 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 half life of incremental atmospheric CO₂ 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.
- Climate modeling.
- Empirical, from climate change over the instrumental record.

Climate models evaluated by comparison with observations are essential to informed decision making.

AEROSOL IN MEXICO CITY BASIN



AEROSOL IN MEXICO CITY BASIN

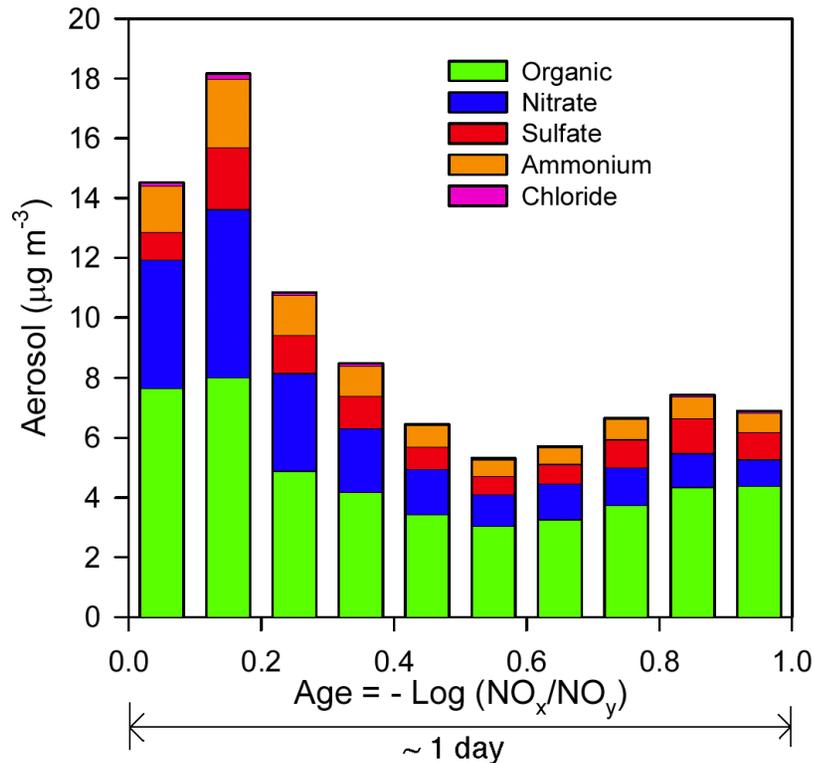


Mexico City is a wonderful place to study aerosol properties and evolution.

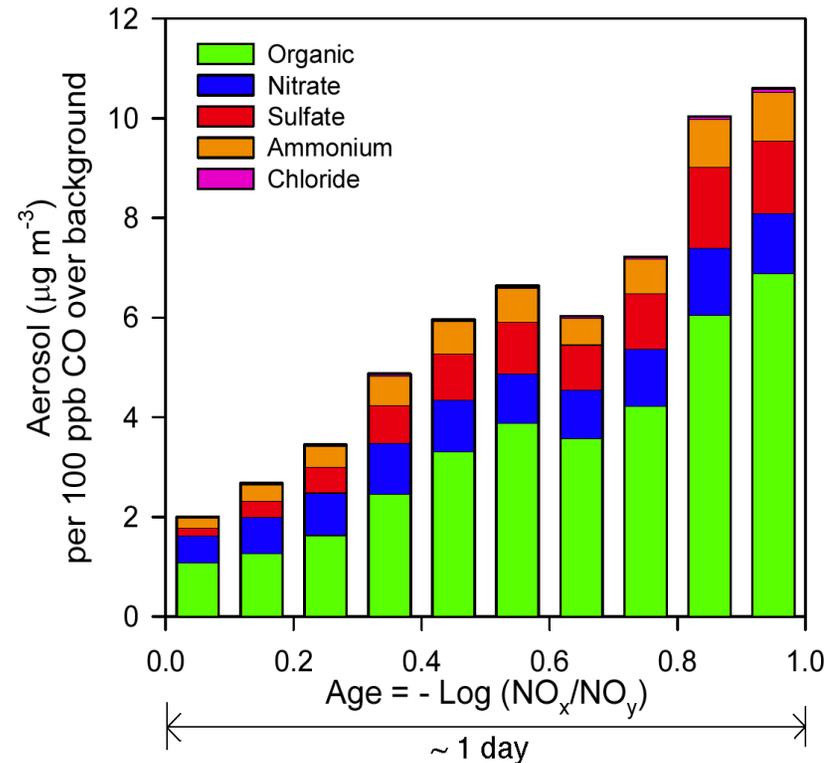
SECONDARY AEROSOL PRODUCTION

Parcel age measured using $-\log(\text{NO}_x/\text{NO}_y)$ as clock

Concentration



Normalized concentration



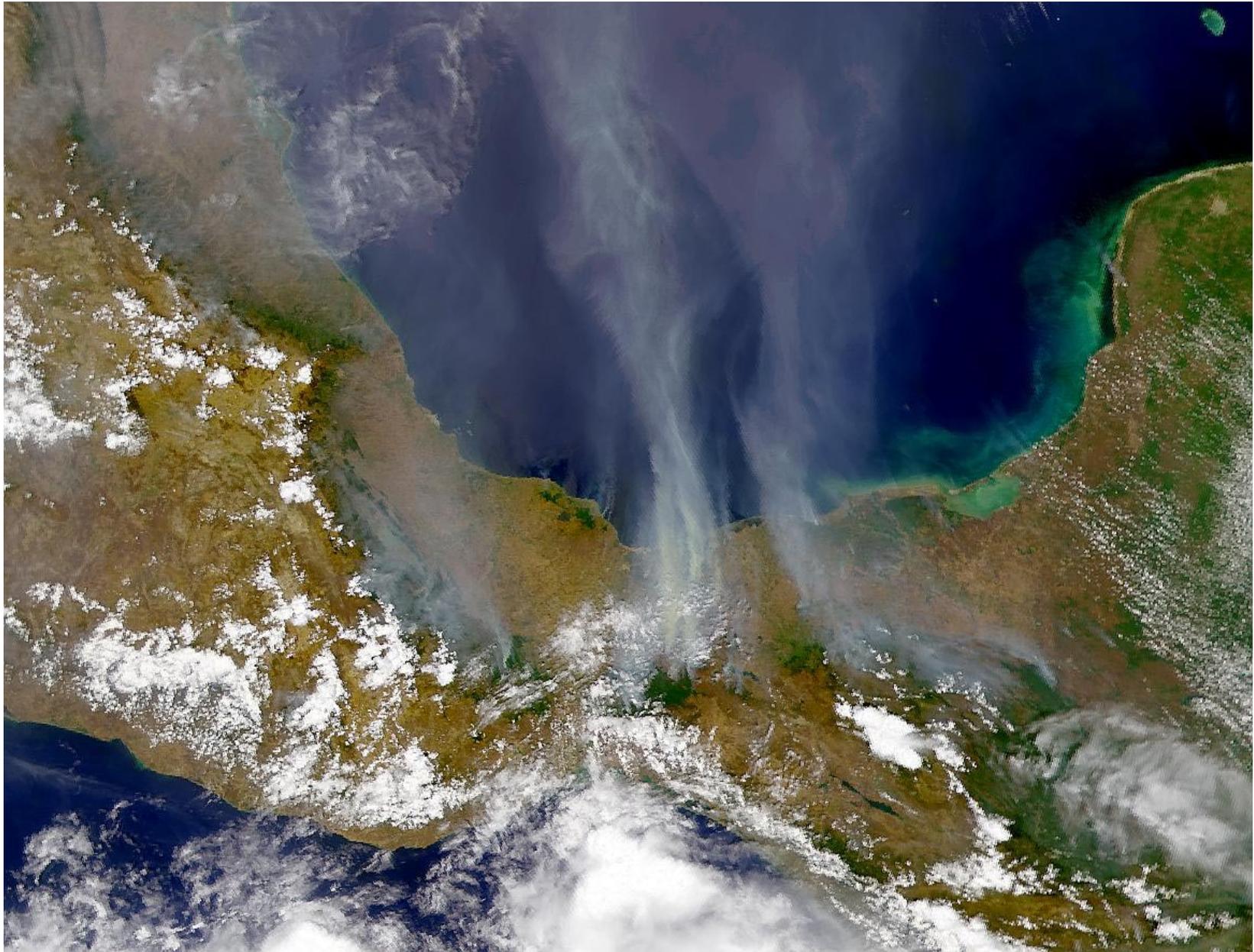
L. Kleinman et al., DOE Atmospheric Science Program, unpublished

Dilution is accounted for by normalizing aerosol concentration to CO above background.

$\sim 5 \times$ increase in total aerosol; $\sim 7 \times$ increase in organic aerosol.

Measured increase in organic aerosol exceeds modeled based on laboratory experiments and measured volatile organic carbon *tenfold*.

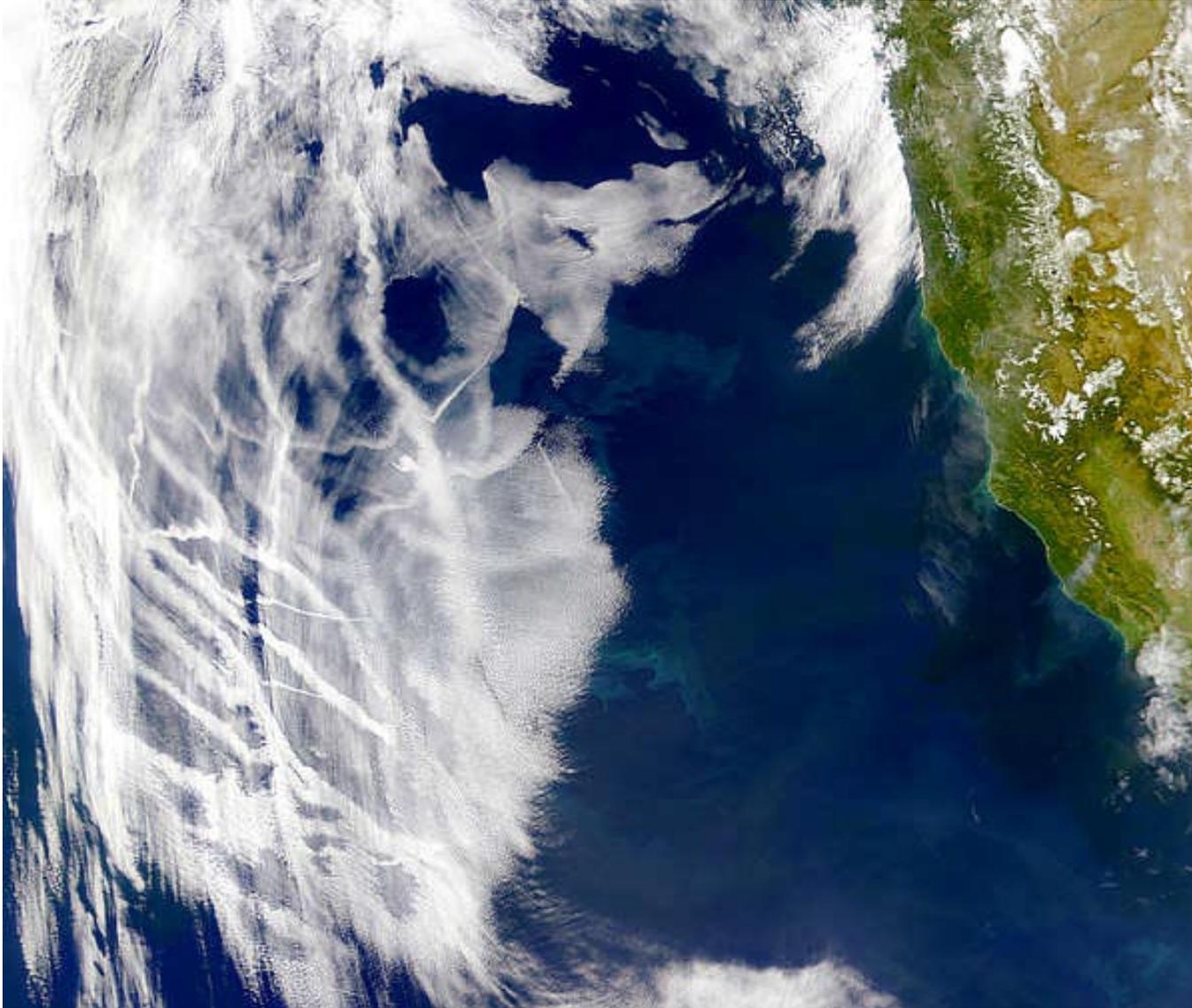
AEROSOLS AS SEEN FROM SPACE



Fire plumes from southern Mexico transported north into Gulf of Mexico.

CLOUD BRIGHTENING BY SHIP TRACKS

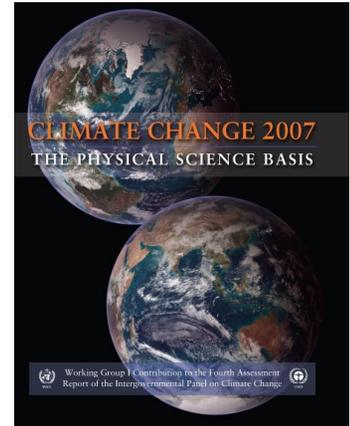
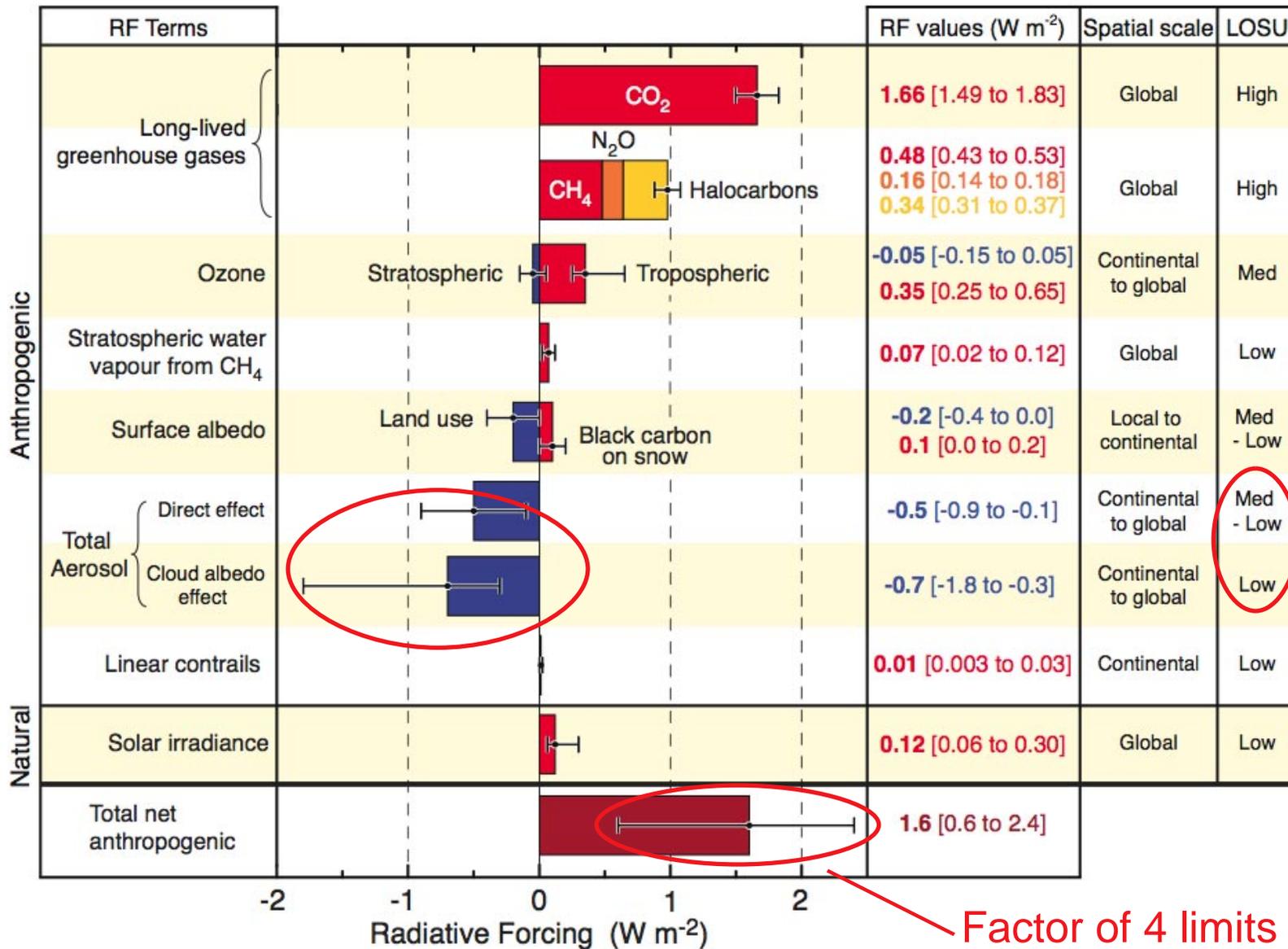
Satellite photo off California coast



Aerosols from ship emissions enhance reflectivity of marine stratus.

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

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



©IPCC 2007: WG1-AR4

Factor of 4 limits empirical inferences and model evaluation.

LOSU denotes level of scientific understanding.

AEROSOL RADIATIVE FORCING

Difference in radiative flux due to aerosols

Instantaneous forcing

- Aerosol present *minus* aerosol absent.
- *Can be measured* (for direct effect), e.g., comparison against Rayleigh sky.

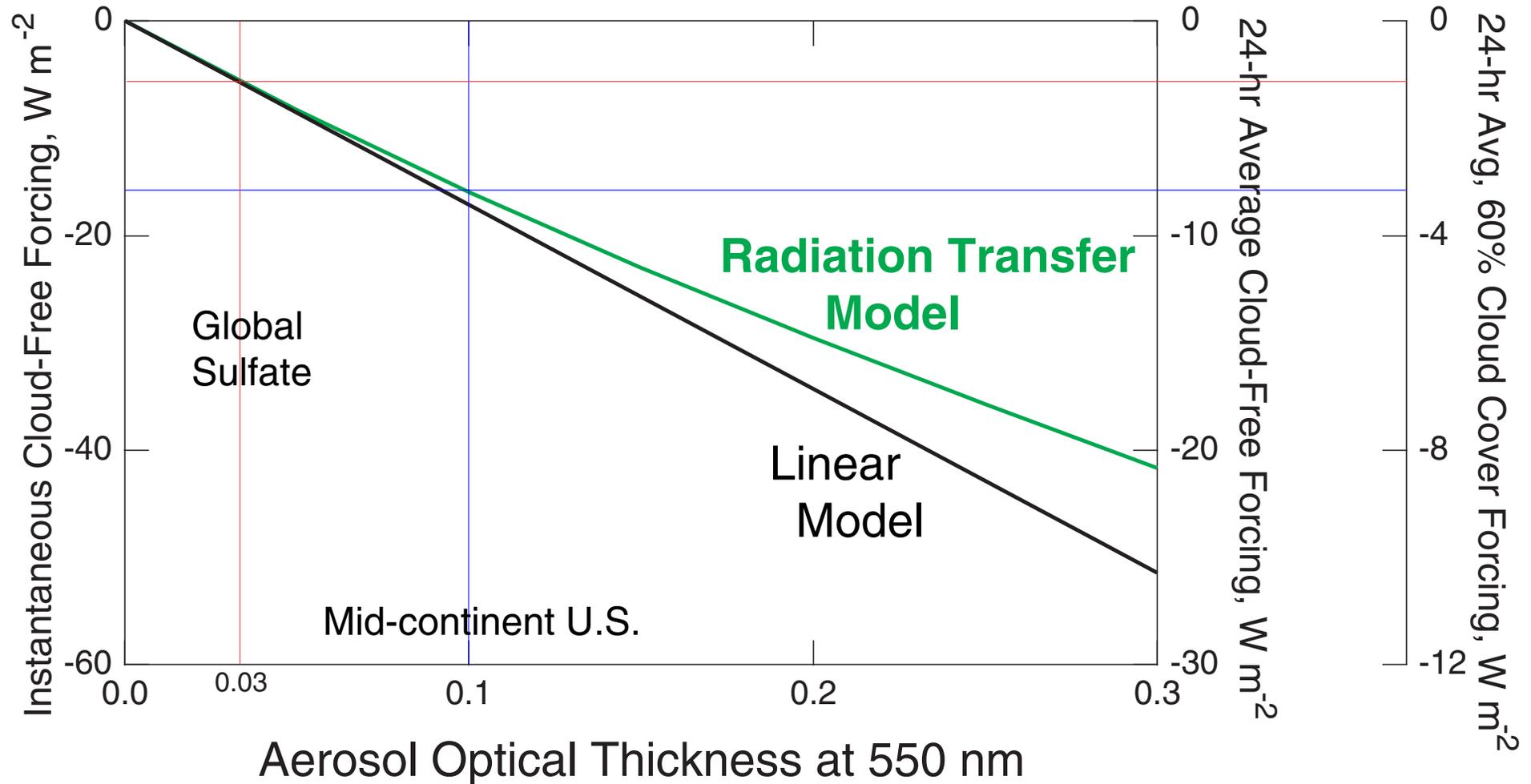
Secular forcing

- Total aerosol *minus* pre-industrial aerosol (function of time).
- *Cannot be measured*; requires attribution of aerosol to natural and anthropogenic sources and understanding of any interactions and nonlinearities.

Determination of aerosol forcing is especially problematic for aerosol indirect effect, which depends on $\log(N/N_0)$.

ESTIMATES OF AEROSOL DIRECT FORCING

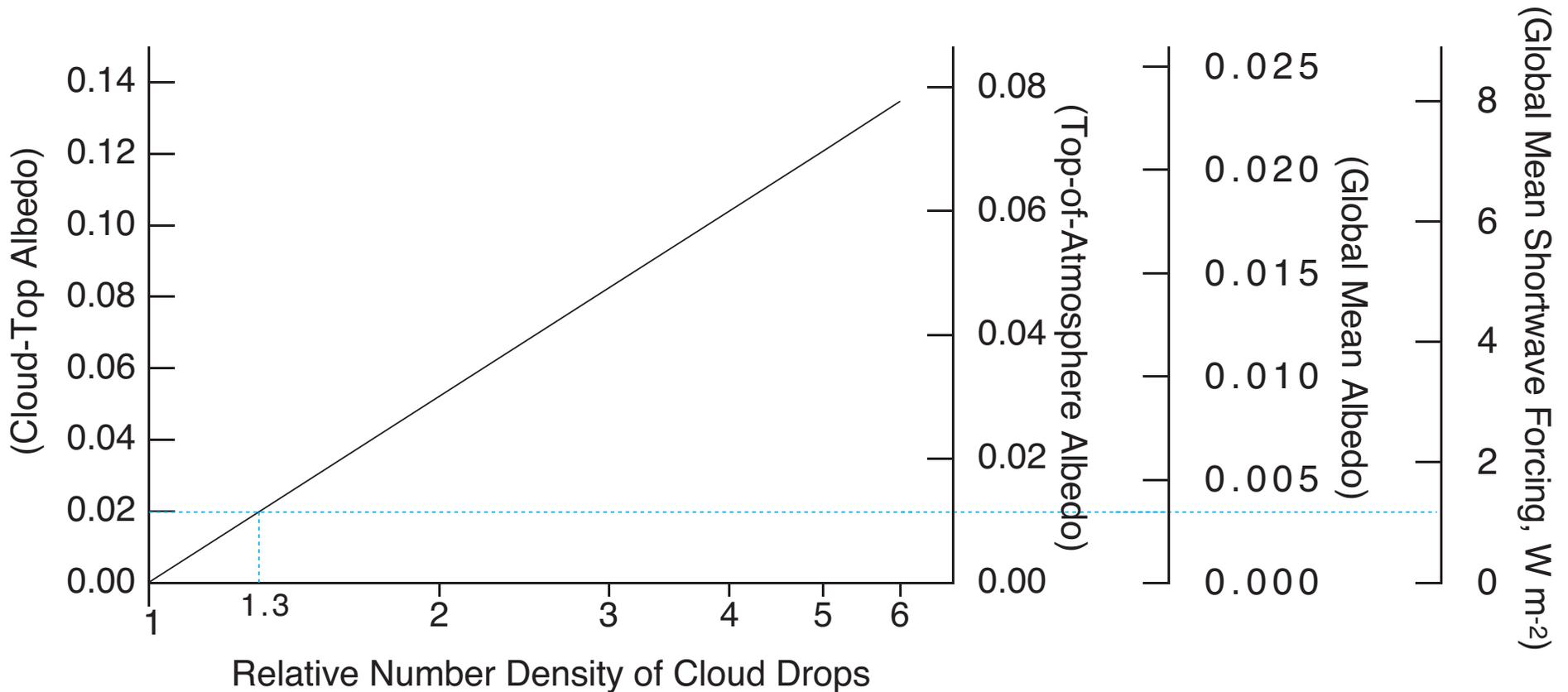
By linear model and by radiation transfer modeling



Global average sulfate optical thickness is 0.03: **$1 W m^{-2}$ cooling.**

In *continental U. S.* typical aerosol optical thickness is 0.1: **$3 W m^{-2}$ cooling.**

SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION



Schwartz and Slingo (1996)

Indirect forcing is highly sensitive to perturbations in cloud drop concentration.

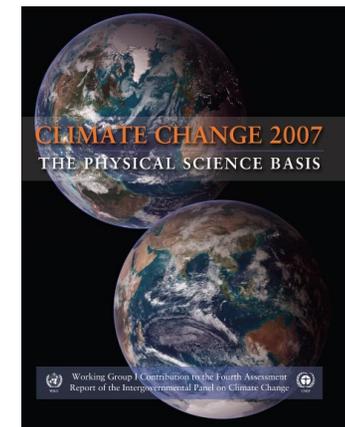
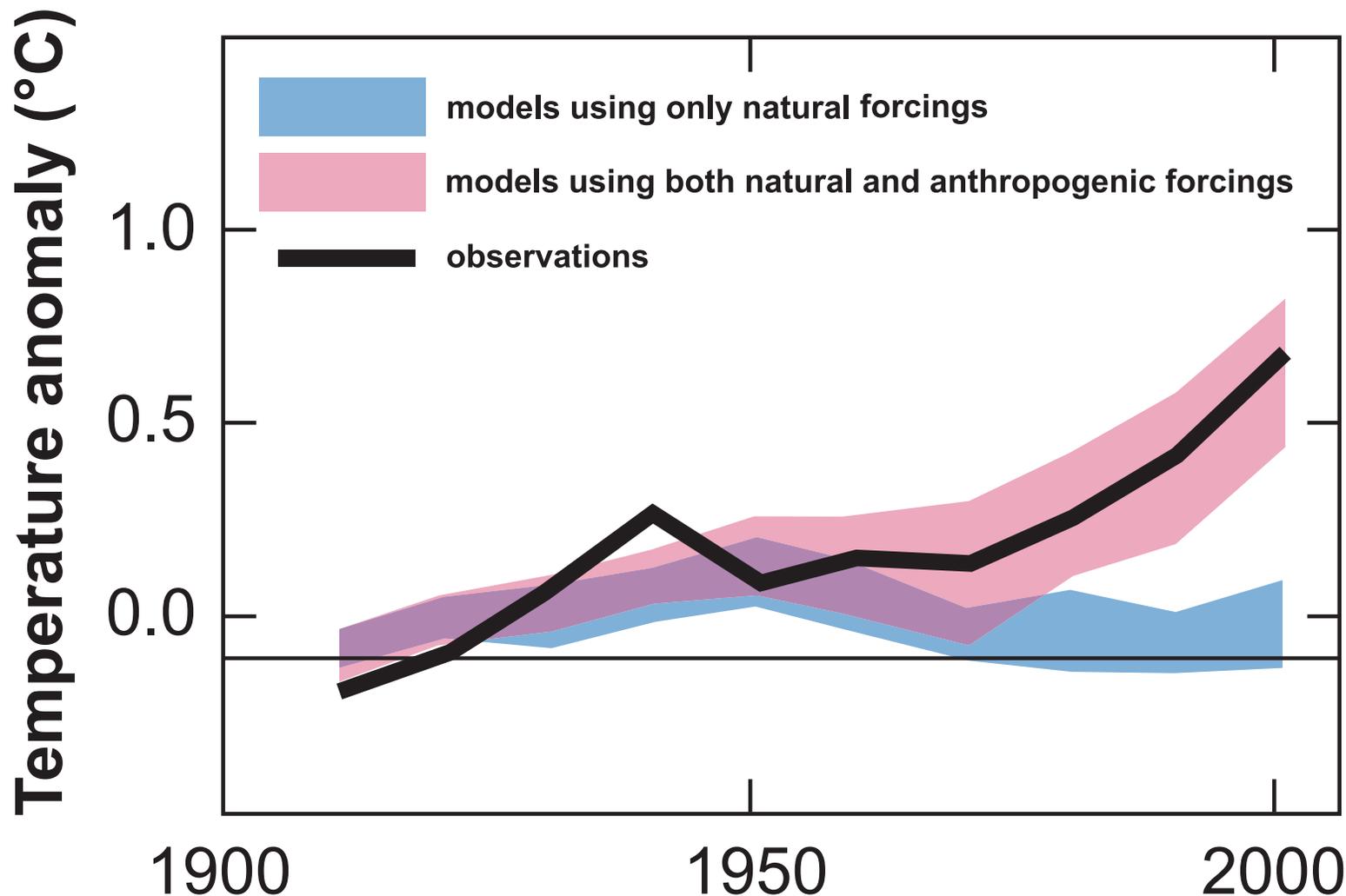
A 30% increase in cloud drop concentration results in a forcing of ~ 1 W m⁻².

IMPORTANCE OF ACCURATE KNOWLEDGE OF SECULAR AEROSOL FORCING

- *Comparable in magnitude* to greenhouse gas forcing.
- *Offsets a substantial but unknown fraction* of greenhouse gas forcing.
- *Similar time history* to greenhouse gas forcing.
- Required as *input to climate models* to assess accuracy over industrial period.
- Uncertainty *confounds interpretation of climate change* over industrial period.
- Uncertainty *limits ability to determine climate sensitivity*.

TOO ROSY A PICTURE?

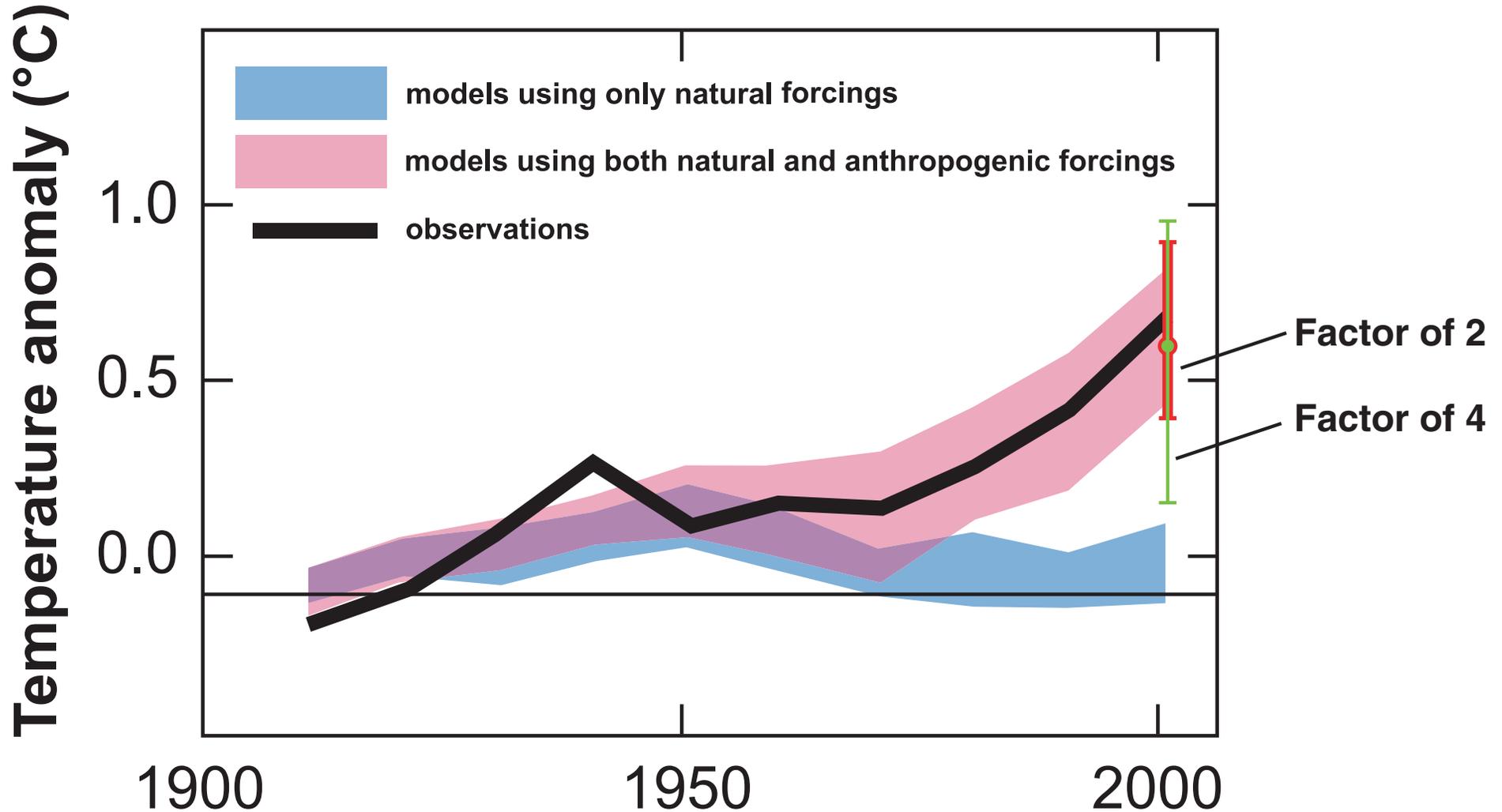
Ensemble of 58 model runs with 14 global climate models



“[M]odels are able to simulate the observed 20th-century changes in temperature when they include all of the most important external factors, including human influences from sources such as greenhouse gases and natural external factors.”

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



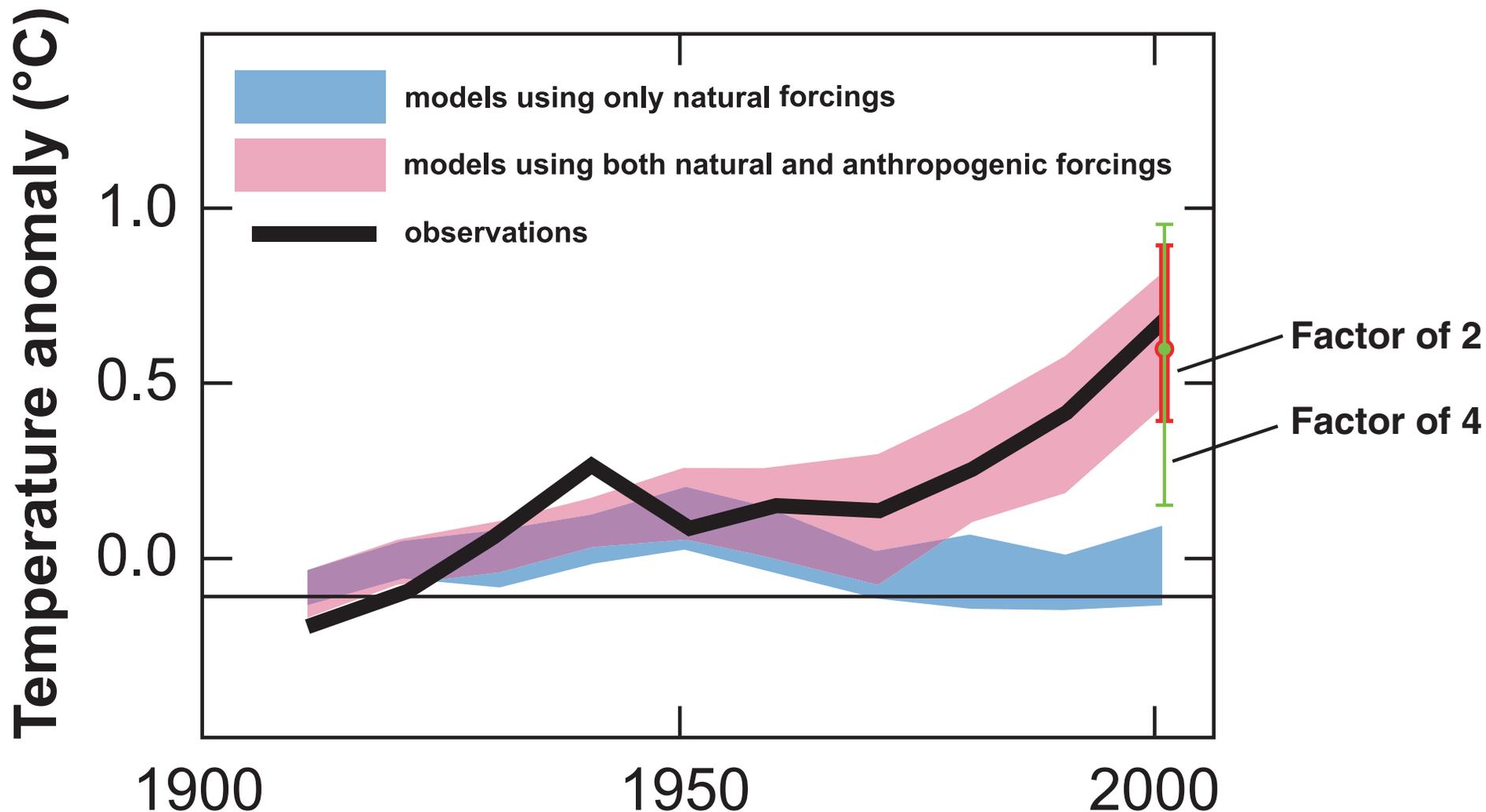
Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007

Uncertainty in modeled temperature increase – less than a factor of 2, red – is well less than uncertainty in forcing – a factor of 4, green.

How can this be?

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models

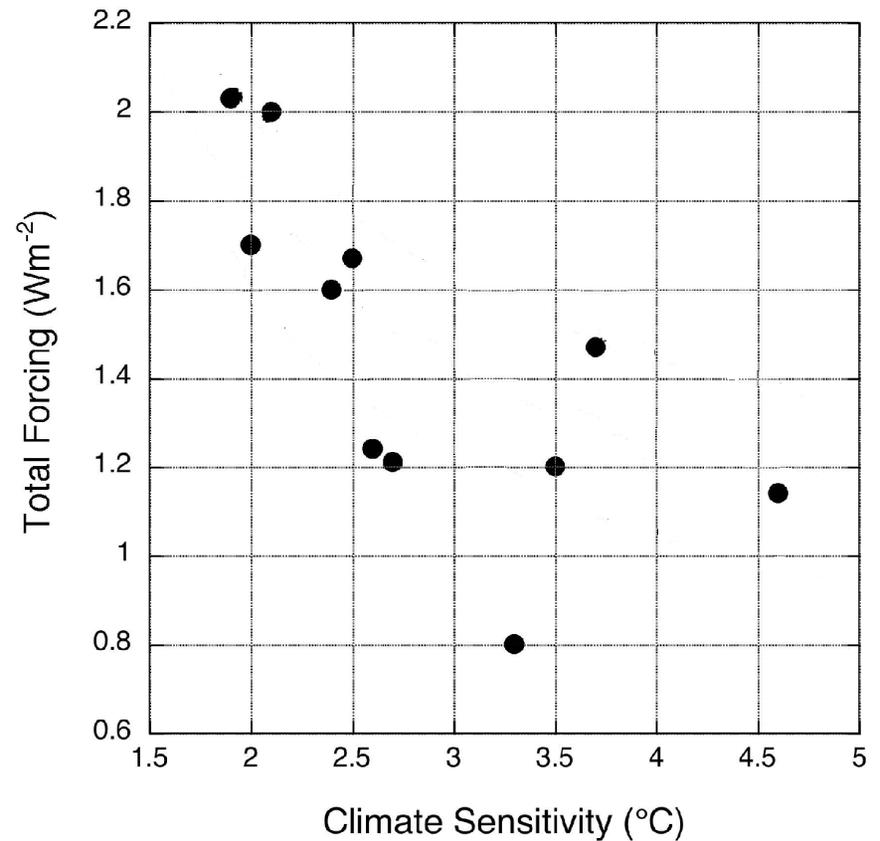
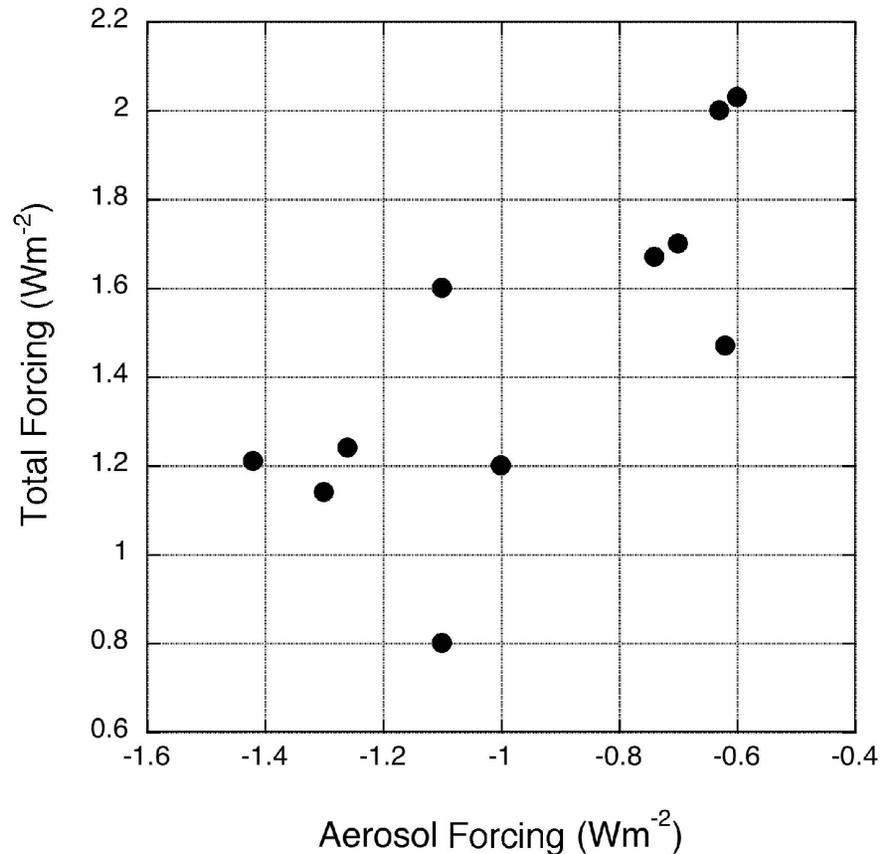


Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007

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



J. Kiehl (NCAR), GRL, in press, 2007

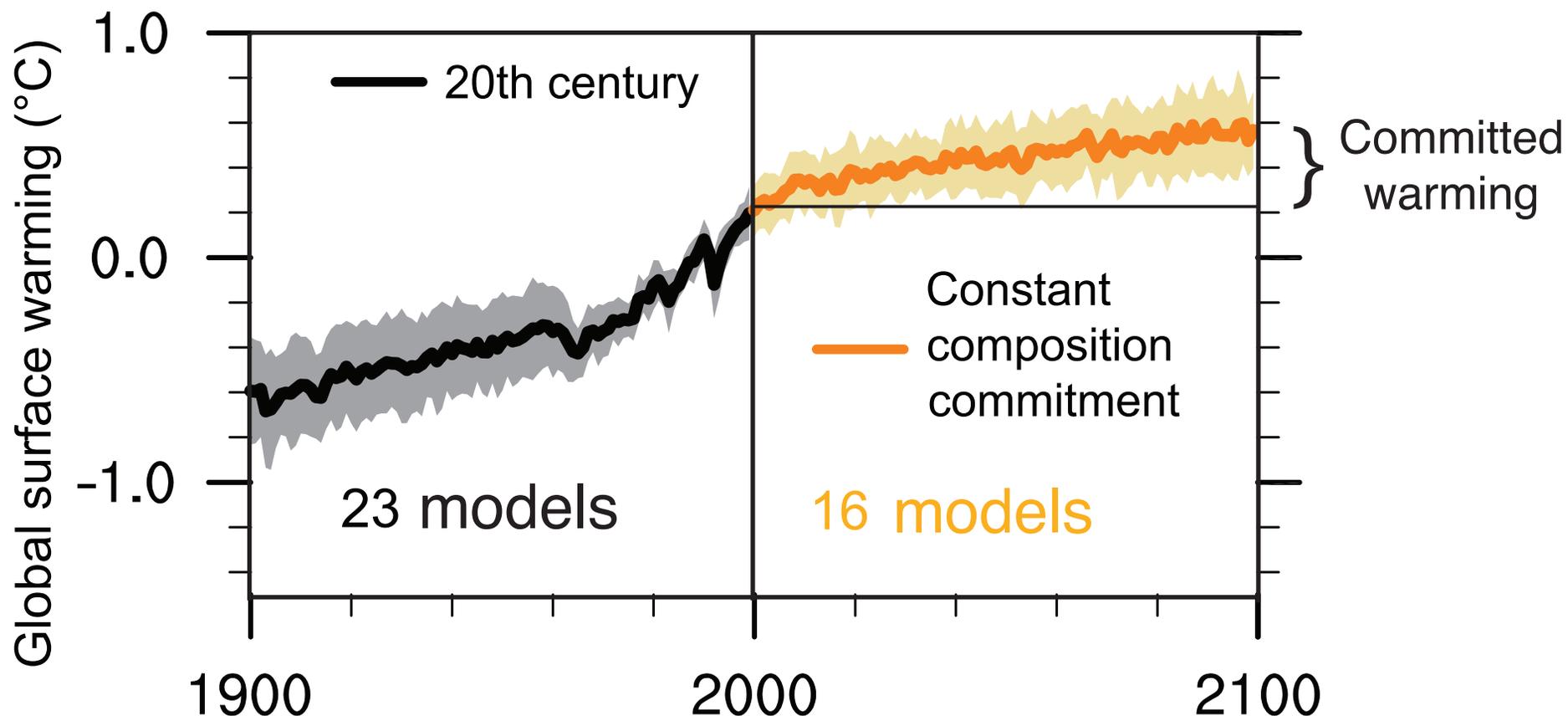
Total forcing increases with decreasing (negative) aerosol forcing.

Climate models with higher sensitivity have lower total forcing.

These models cannot all be correct.

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.”

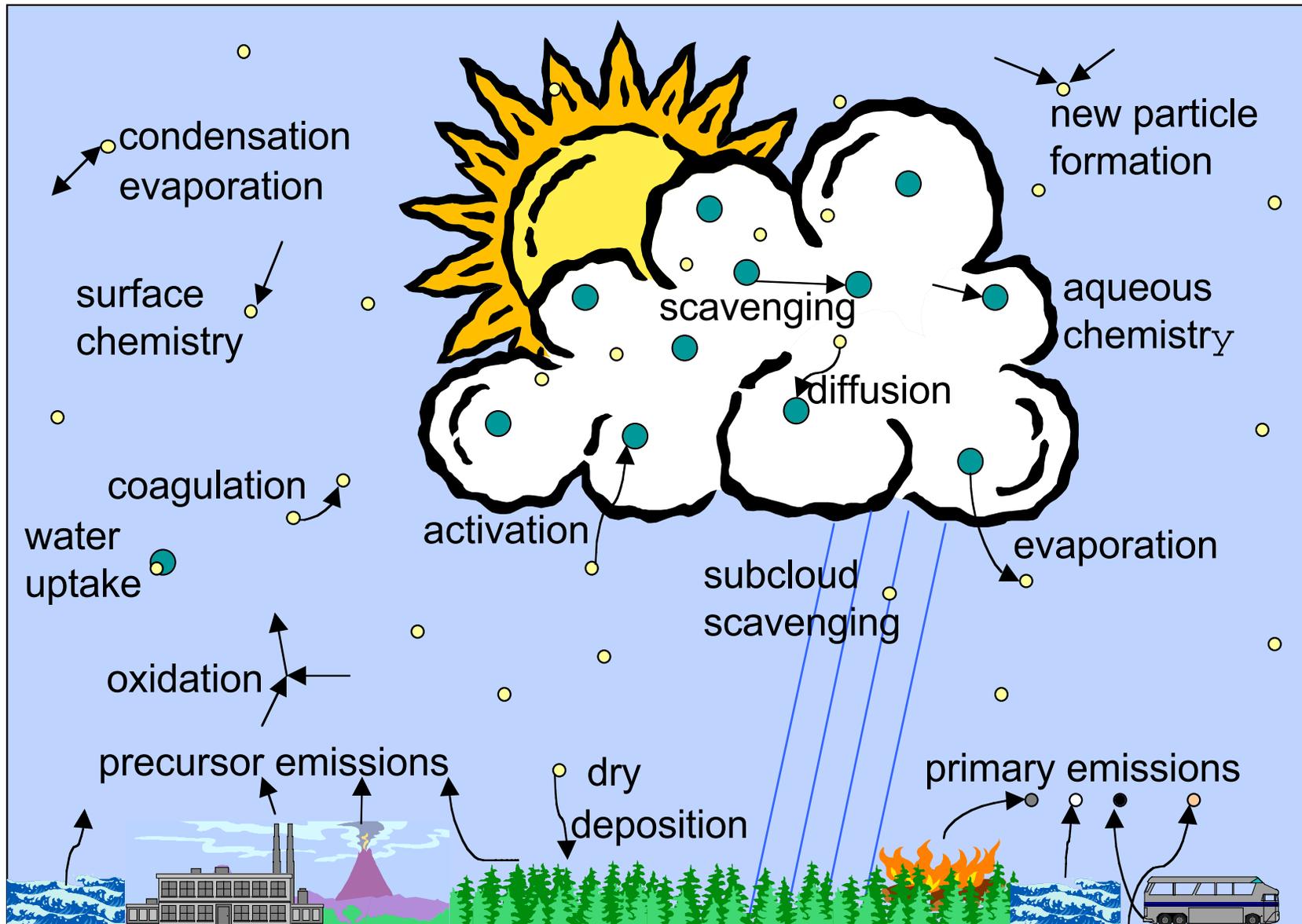
Wigley, Science, 2005

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

“Because of the long time scale required for removal of CO₂ 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 CO₂ emissions were immediately cut to zero; that is, there is a *commitment to additional CO₂-induced warming* even in the absence of emissions.

Friedlingstein and Solomon, PNAS, 2005

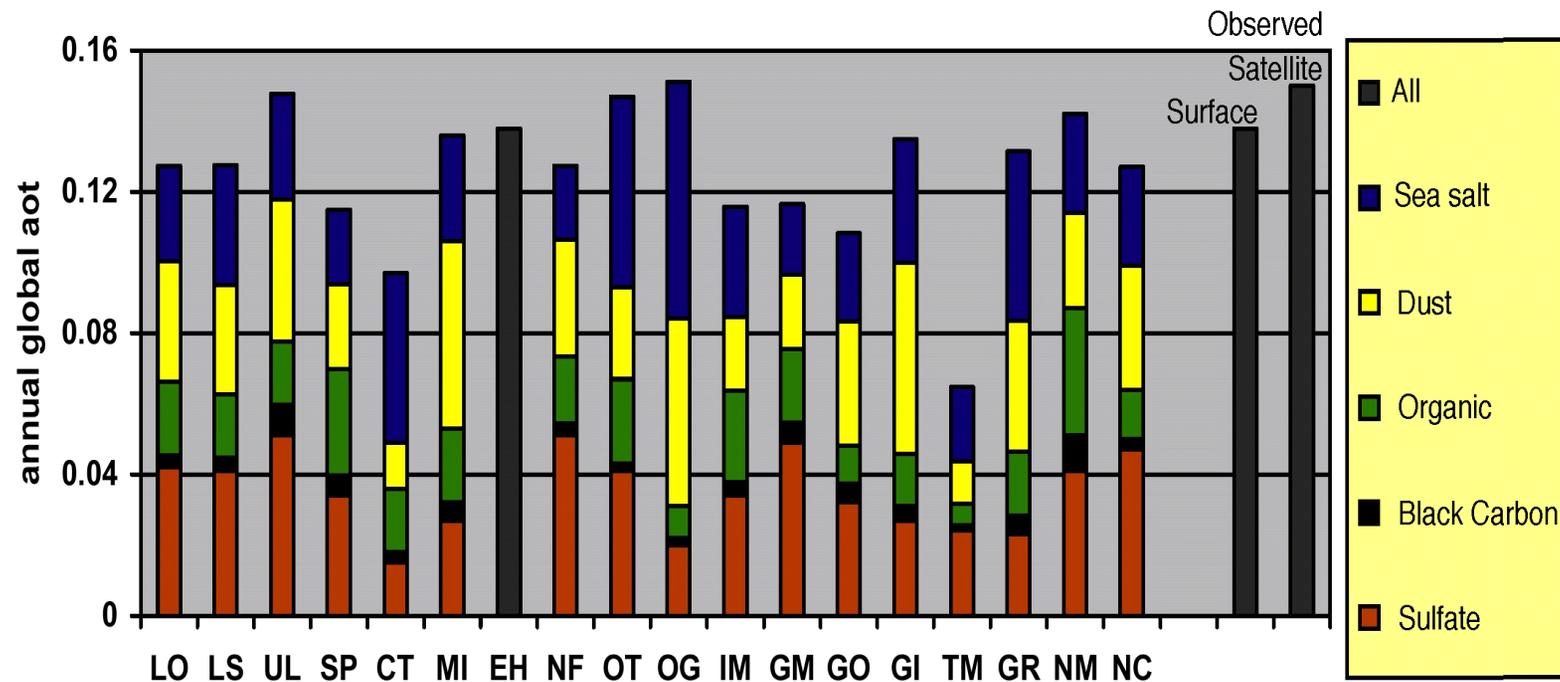
AEROSOL PROCESSES THAT MUST BE UNDERSTOOD AND REPRESENTED IN MODELS



Ghan and Schwartz, Bull. Amer. Meteorol. Soc., 2007

AEROSOL OPTICAL DEPTH IN 18 MODELS (AEROCOM)

Comparison also with surface and satellite observations



Kinne et al., ACP, 2006

Surface measurements: AERONET network.

Satellite measurements: composite from multiple instruments/platforms.

Are the models getting the “right” answer for the wrong reason?

Are the models getting the “right” answer because the answer is known?

Are the satellites getting the “right” answer because the answer is known?

ALTERNATIVE,
COMPLEMENTARY APPROACH:

EMPIRICAL DETERMINATION
OF EARTH'S CLIMATE
SENSITIVITY

ENERGY BALANCE MODELS



Heat capacity, time constant, and sensitivity of Earth's climate system

Stephen E. Schwartz¹

Received 3 April 2007; revised 14 June 2007; accepted 10 July 2007; published XX Month 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 $14 \pm 6 \text{ W a m}^{-2} \text{ K}^{-1}$, equivalent to 110 m of ocean water; other sinks raise the effective planetary heat capacity to $17 \pm 7 \text{ W a m}^{-2} \text{ K}^{-1}$ (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 $5 \pm 1 \text{ a}$. The resultant equilibrium climate sensitivity, $0.30 \pm 0.14 \text{ K}/(\text{W m}^{-2})$, corresponds to an equilibrium temperature increase for doubled CO_2 of $1.1 \pm 0.5 \text{ K}$. 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, $0.57 \pm 0.08 \text{ K}$, as $1.9 \pm 0.9 \text{ W m}^{-2}$. For this forcing considered the sum of radiative forcing by incremental greenhouse gases, $2.2 \pm 0.3 \text{ W m}^{-2}$, and other forcings, other forcing agents, mainly incremental tropospheric aerosols, are inferred to have exerted only a slight forcing over the twentieth century of $-0.3 \pm 1.0 \text{ W m}^{-2}$.

Citation: Schwartz, S. E. (2007), Heat capacity, time constant, and sensitivity of Earth's climate system, *J. Geophys. Res.*, 112, XXXXXX, doi:10.1029/2007JD008746.

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

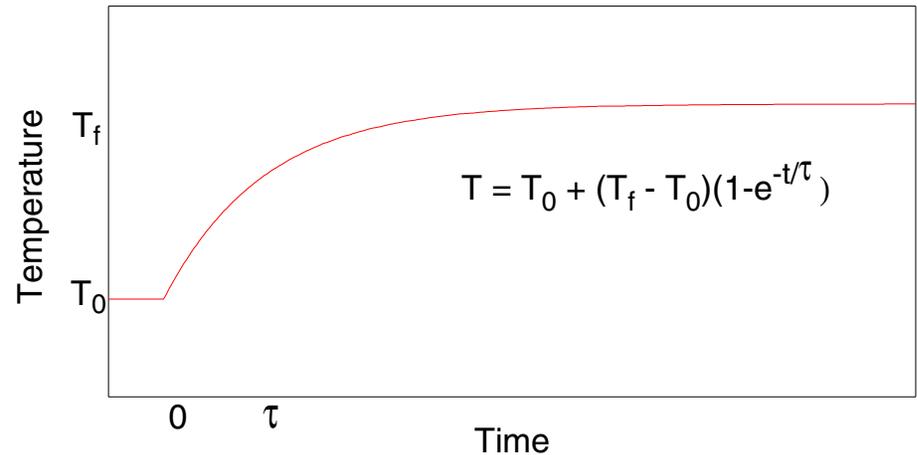
Steady State T : $T_{\infty} = T_{\text{amb}} + \frac{Q}{k}$

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

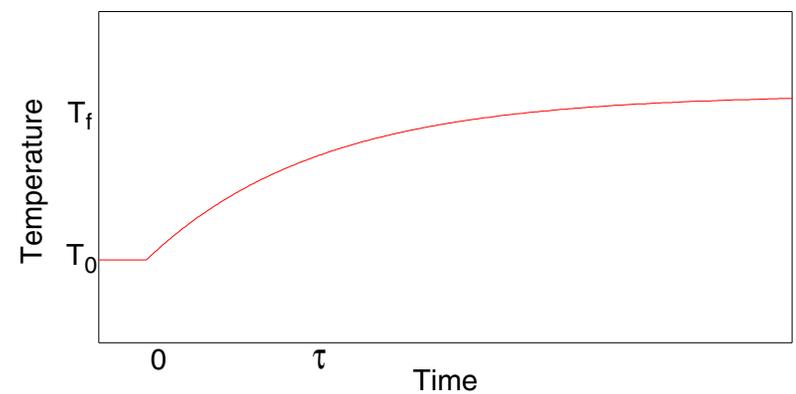
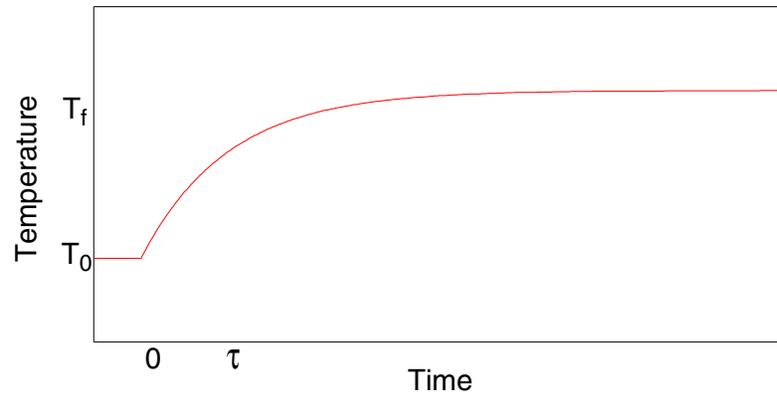
Sensitivity: $\lambda^{-1} \equiv \frac{\Delta T_{\infty}}{F} = \frac{1}{k}$

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

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

$$\text{Initially } Q_0 = \sigma T_0^4$$

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

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

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

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 $\lambda_{S-B}^{-1} = 0.27 \text{ K}/(\text{W m}^{-2})$

For $2 \times \text{CO}_2$ forcing $F_{2\times} = 3.71 \text{ W m}^{-2}$, $\Delta T_{2\times} = 1.0 \text{ K}$

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

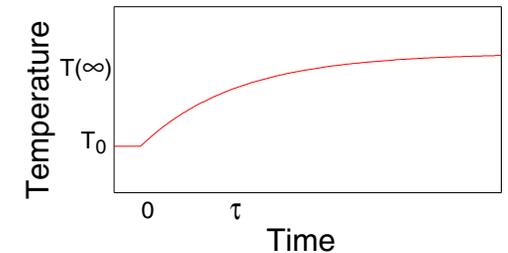
ε is effective emissivity

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 $\lambda^{-1} = f \frac{T_0}{4\gamma_0 J_S} \quad \text{K} / (\text{W m}^{-2})$

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

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

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

One equation in three unknowns

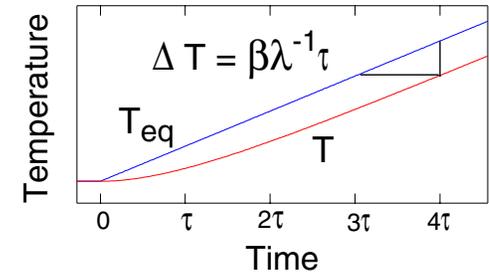
TEMPERATURE RESPONSE TO LINEARLY INCREASING FORCING



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

Energy balance: $C \frac{dT_s}{dt} = \beta t + \gamma J_S - \epsilon \sigma T_s^4$

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 $t/\tau \geq 3$, $\Delta T_s(t) = \beta \lambda^{-1} (t - \tau)$

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

DETERMINING EARTH'S
HEAT CAPACITY
BY OCEAN CALORIMETRY

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

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

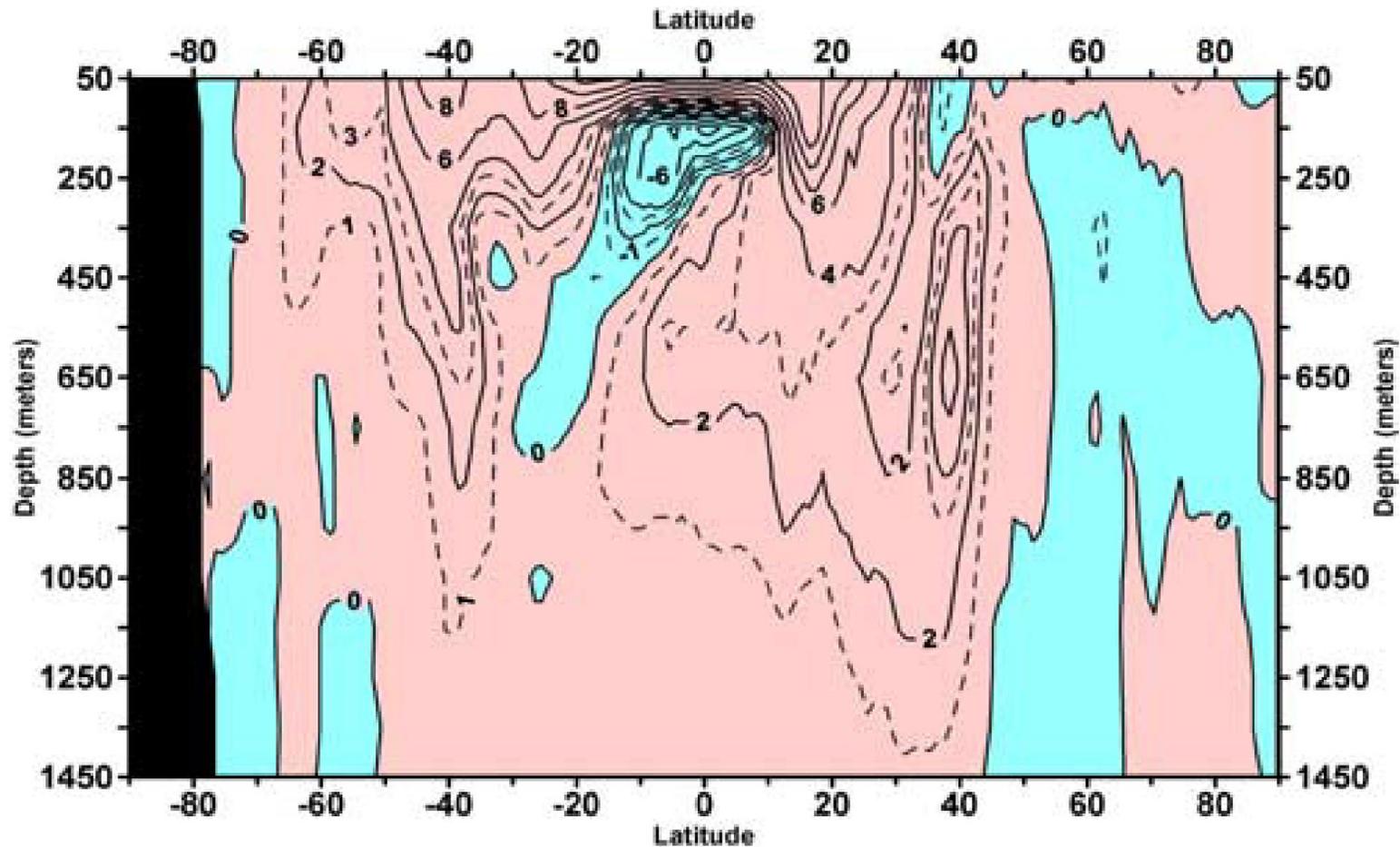
C : Global heat capacity

H : Global ocean heat content

T_s : Global mean surface temperature

ZONAL AVERAGE HEAT CONTENT TREND (1955-2003)

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



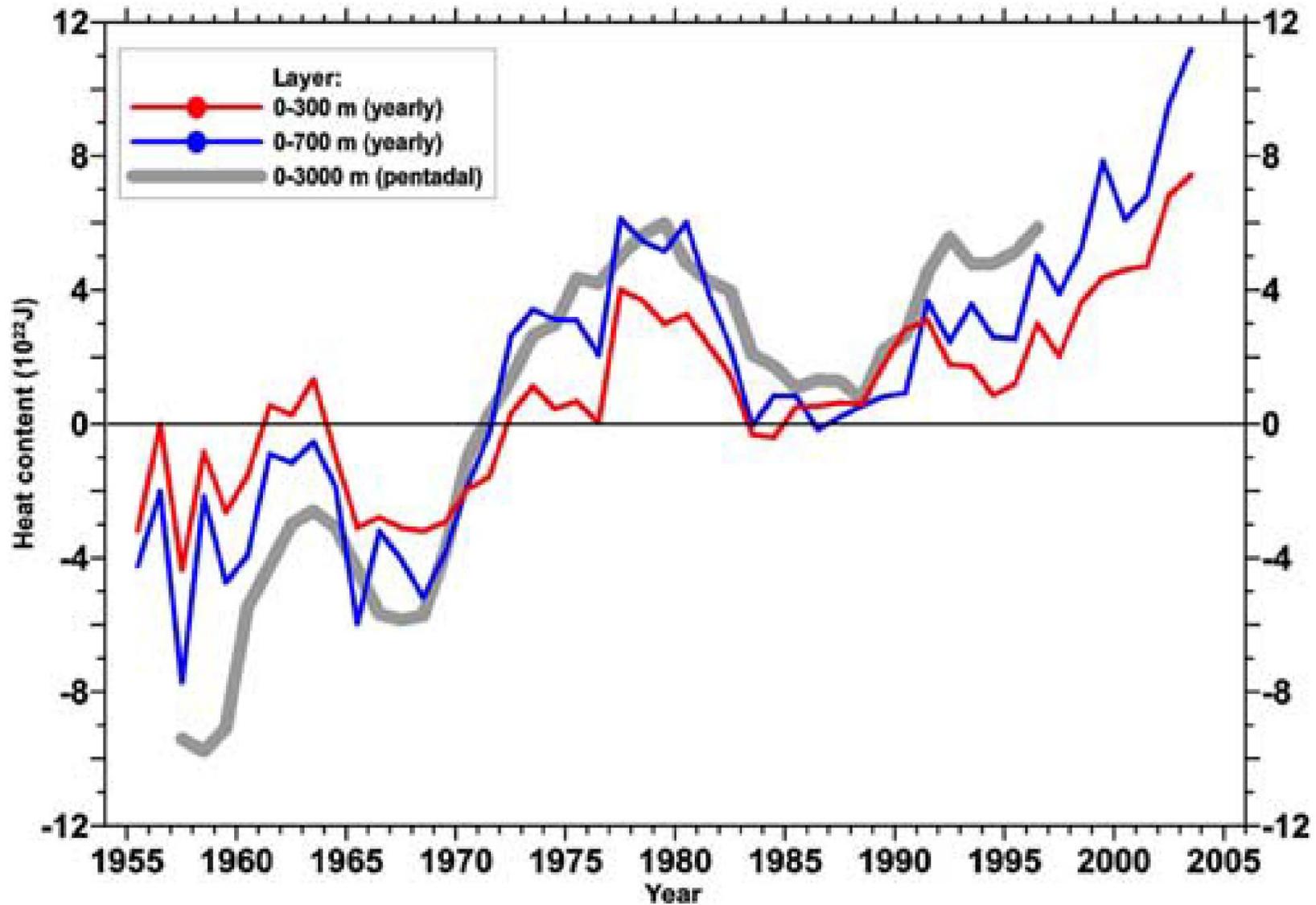
- Heating is greatest in upper ocean, with downwelling plumes.

Warming of the world ocean, 1955–2003

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

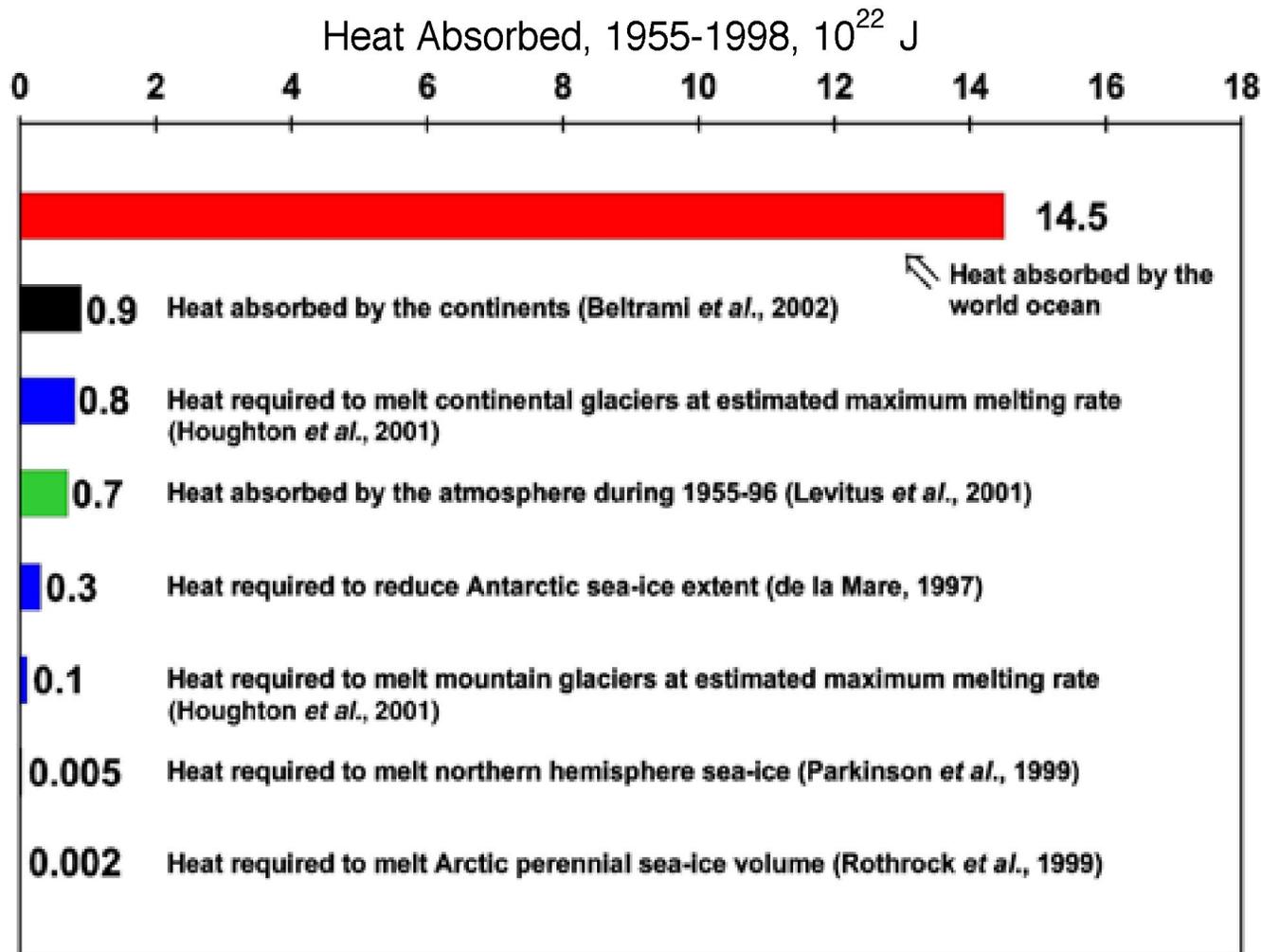
GEOPHYSICAL RESEARCH LETTERS, VOL. 32, 2005

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



Levitus et al., 2005

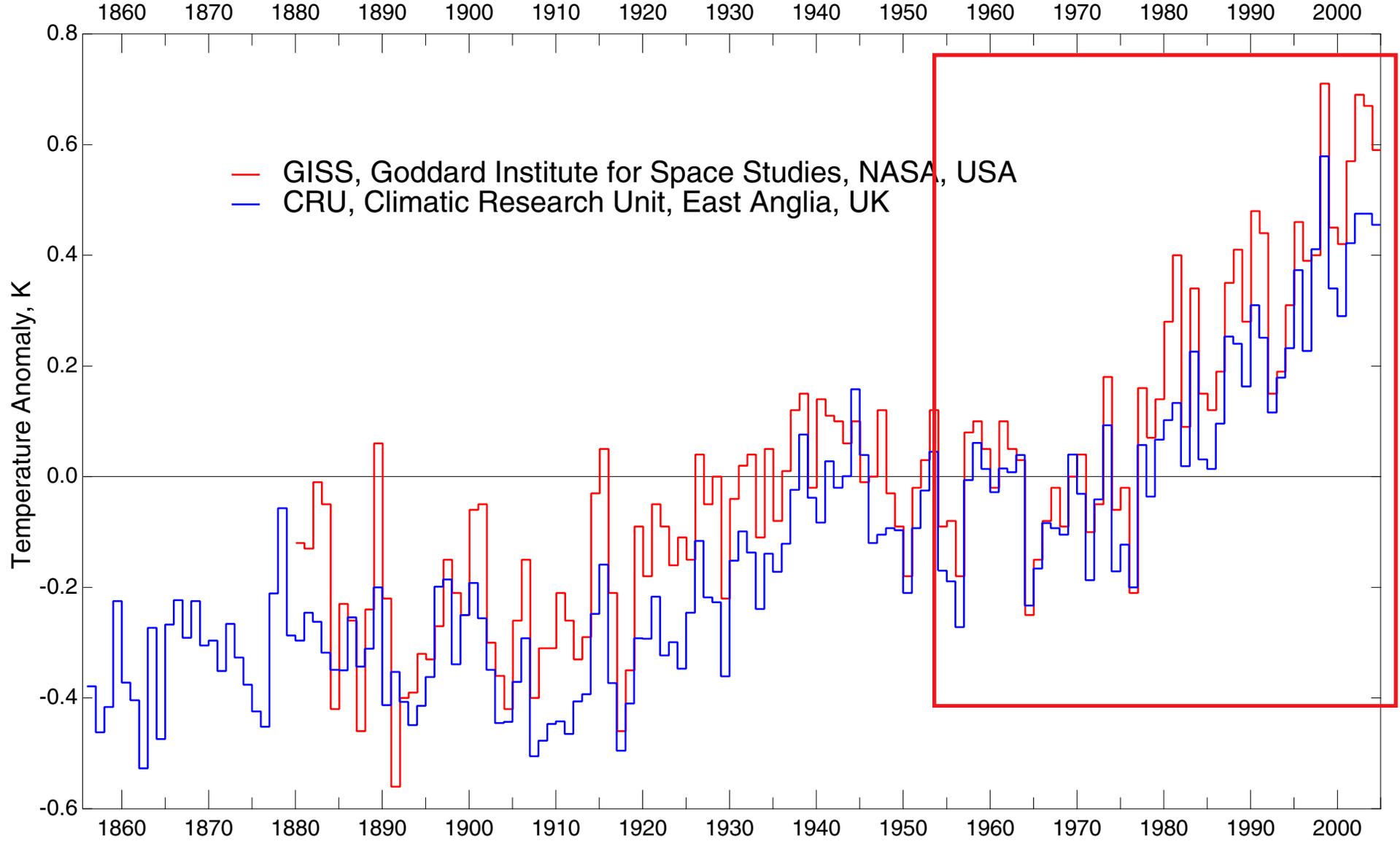
HEAT ABSORPTION BY COMPONENTS OF EARTH'S CLIMATE SYSTEM



The world ocean is responsible for $\sim 84\%$ of the increase in global heat content.

Levitus et al., 2005

GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD

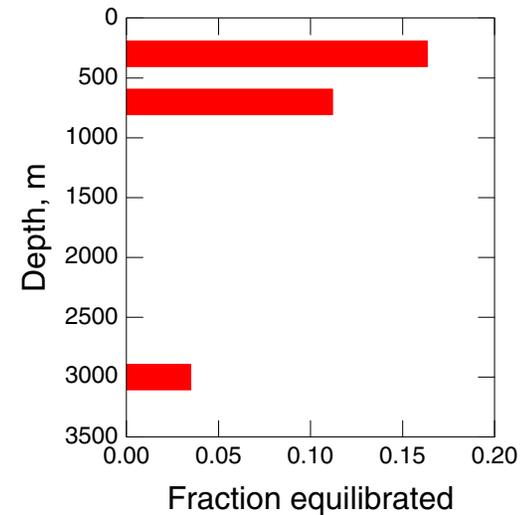
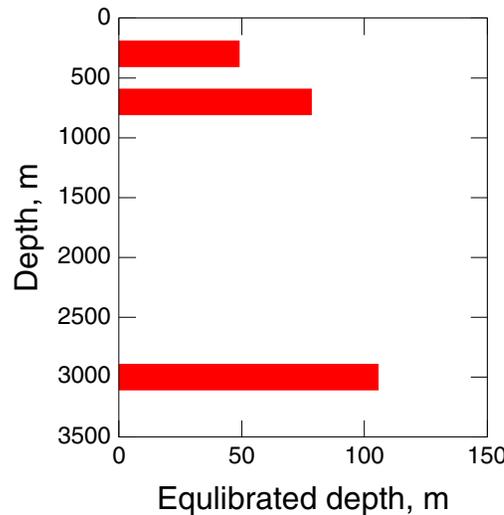
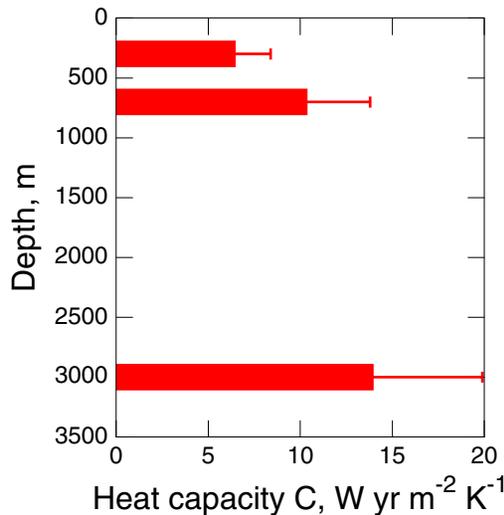
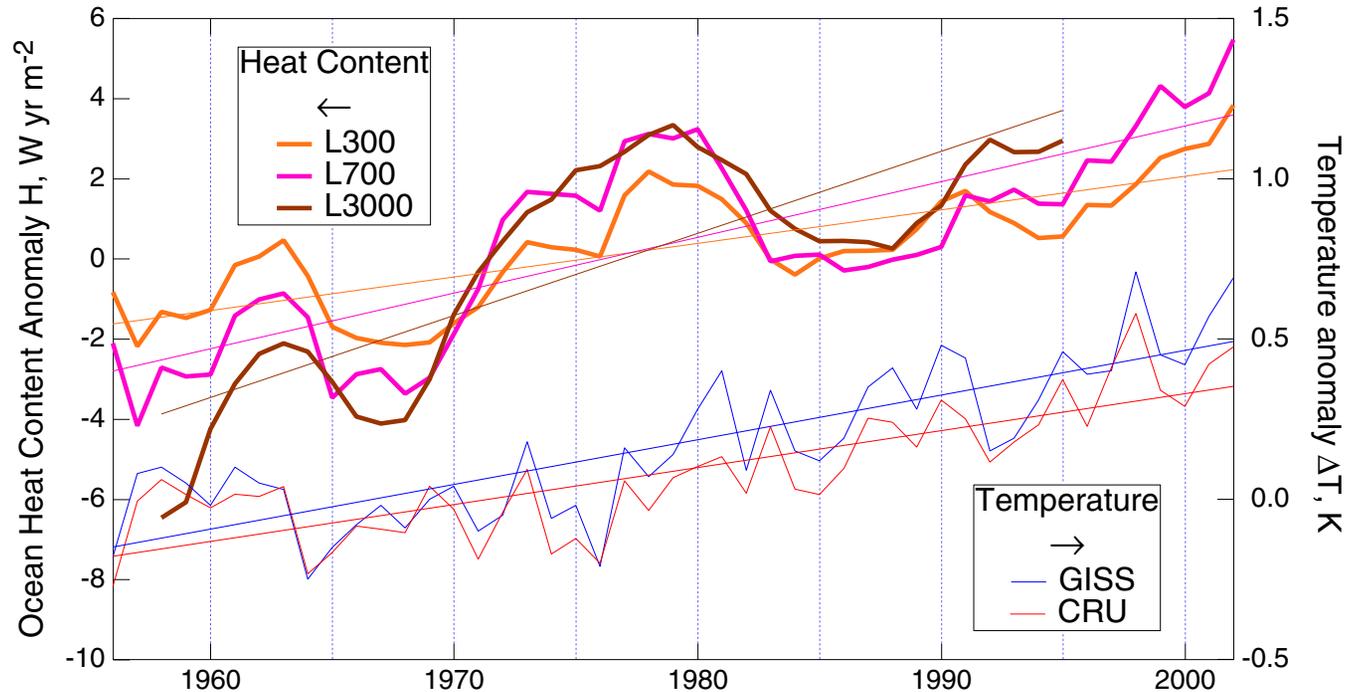


EMPIRICAL DETERMINATION OF OCEAN HEAT CAPACITY

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

Surface temperature T_S :
GISS, CRU

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

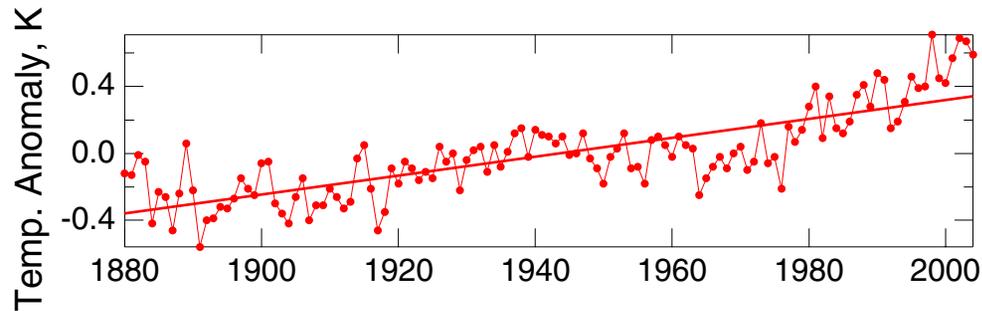


- ~50% of heat capacity is between surface and 300 m.
- Other heat sinks raise global heat capacity to $17 \pm 7 \text{ W yr m}^{-2} \text{ K}^{-1}$.

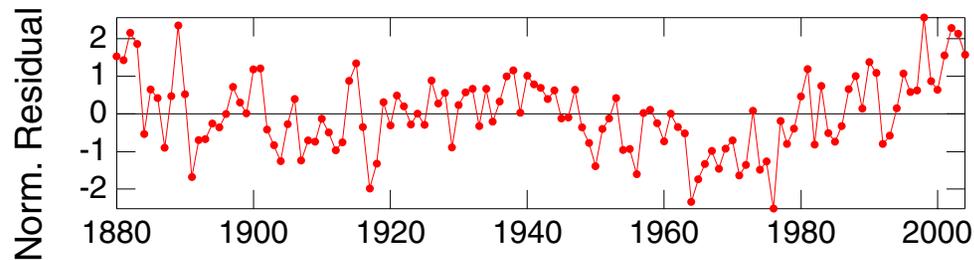
CHARACTERISTIC TIME OF EARTH'S CLIMATE SYSTEM FROM TIME SERIES ANALYSIS

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

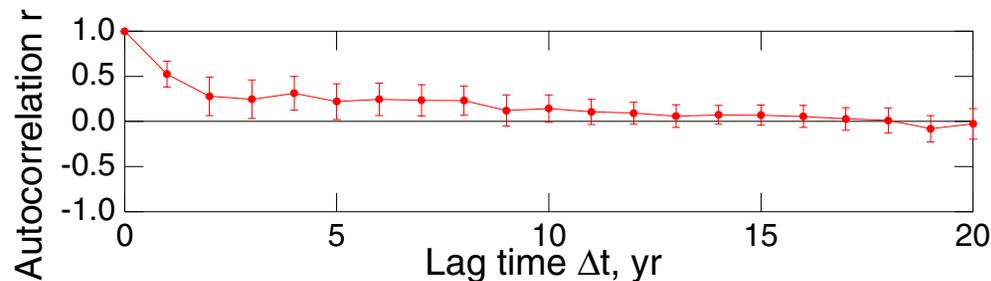
Recipe (GISS annual global mean surface temperature anomaly T_s)



1. Remove long term trend; plot the residuals:

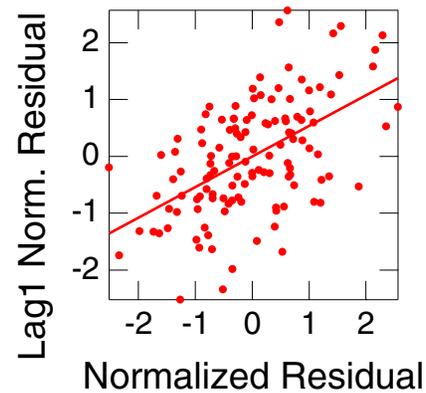


2. Calculate autocorrelogram (& standard deviations; Bartlett, 1948):

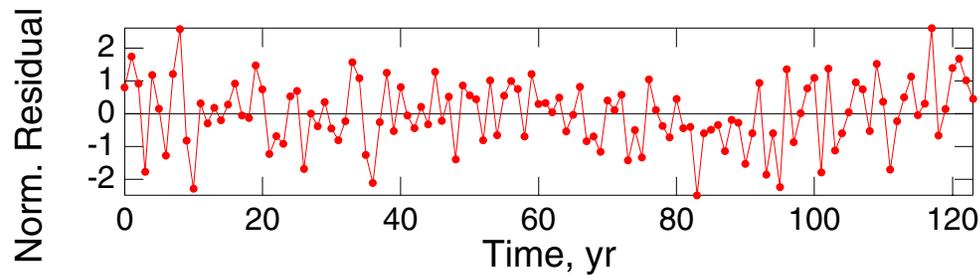


Recipe for determining climate system time constant, continued

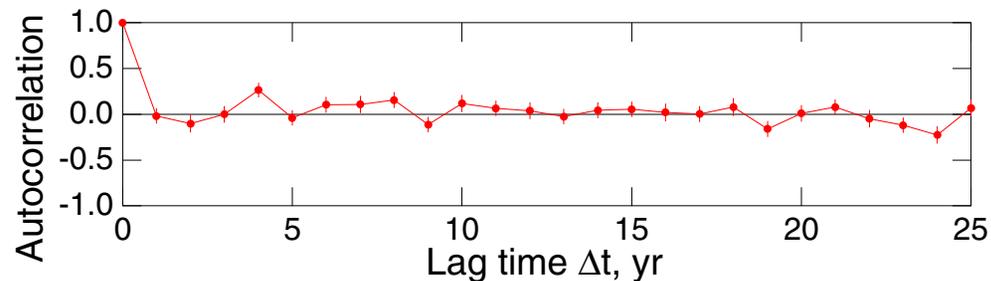
3. Examine the *lag-1* autocorrelation:



4. Remove the trend; plot the residuals:



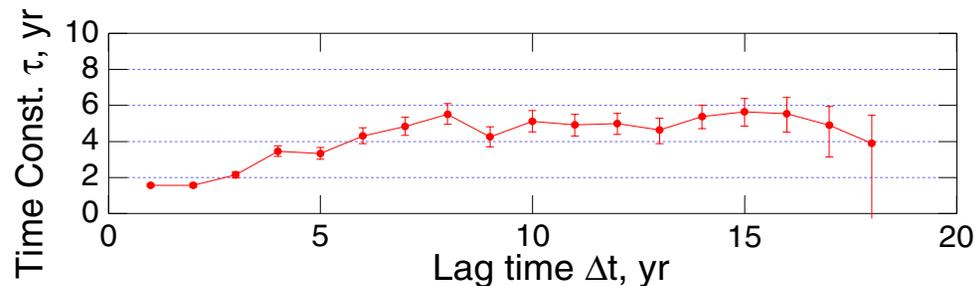
5. Examine for any remaining autocorrelation:



Recipe for determining climate system time constant, continued

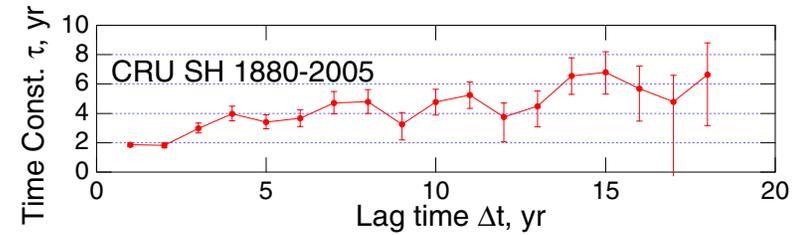
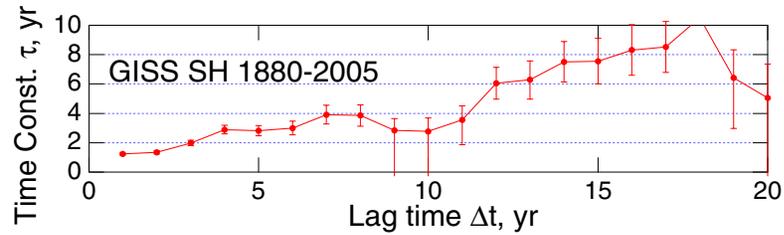
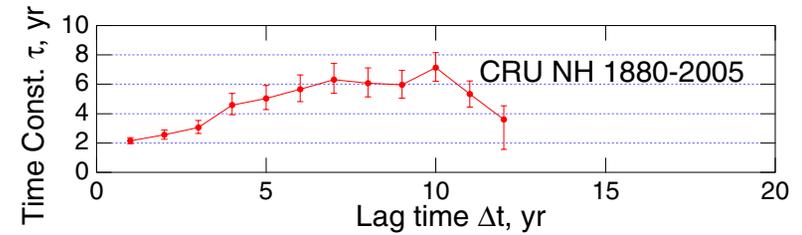
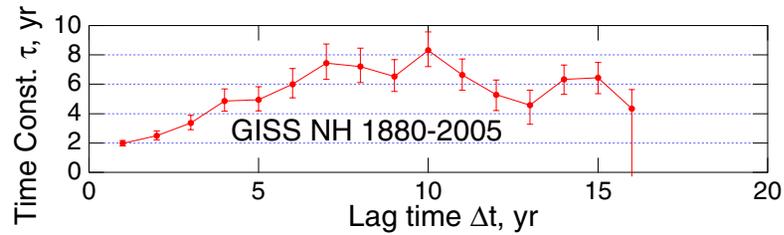
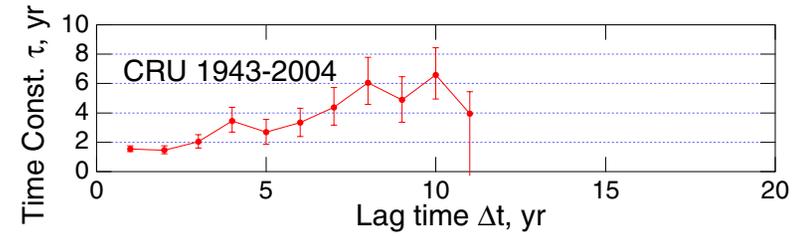
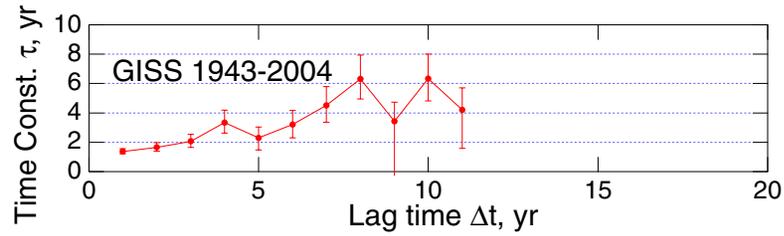
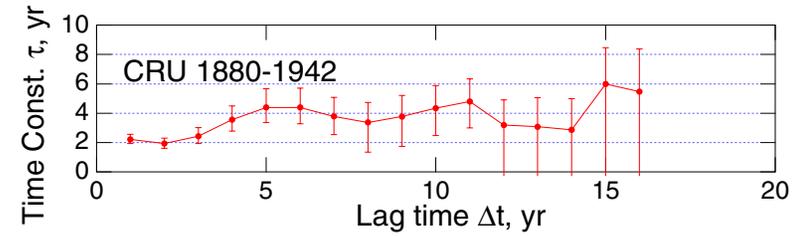
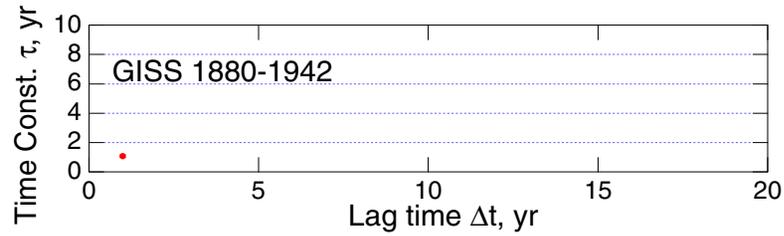
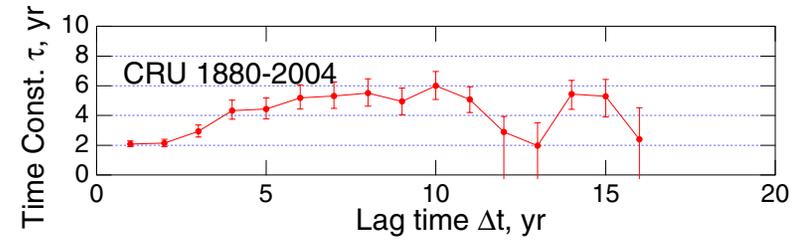
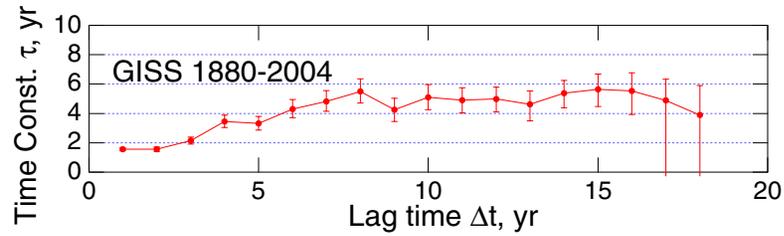
6. If no residual autocorrelation (Markov process) calculate time constant τ for relaxation of system to perturbation:

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



- 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



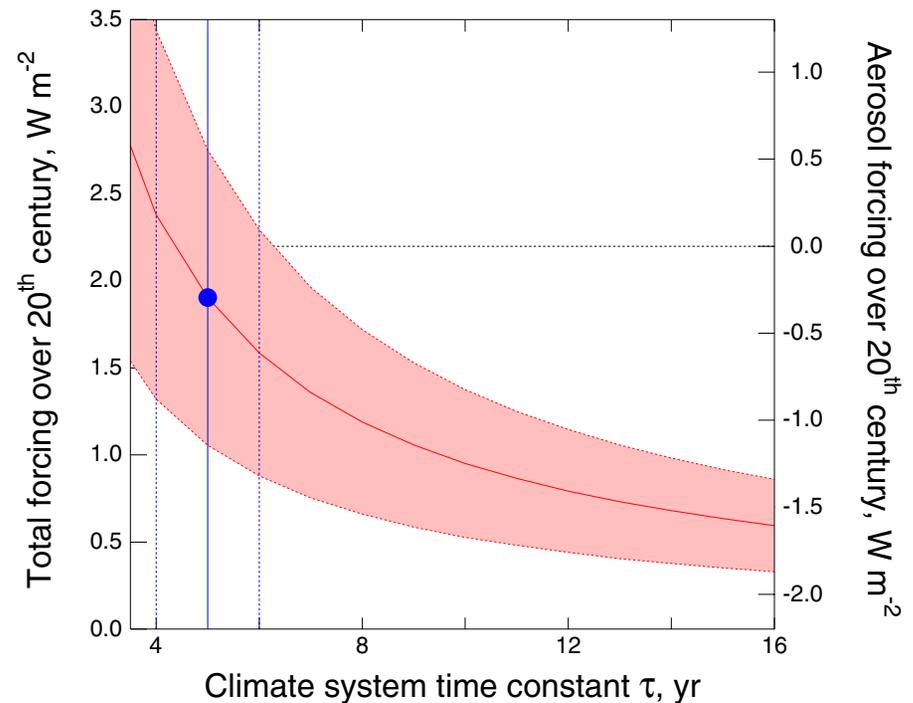
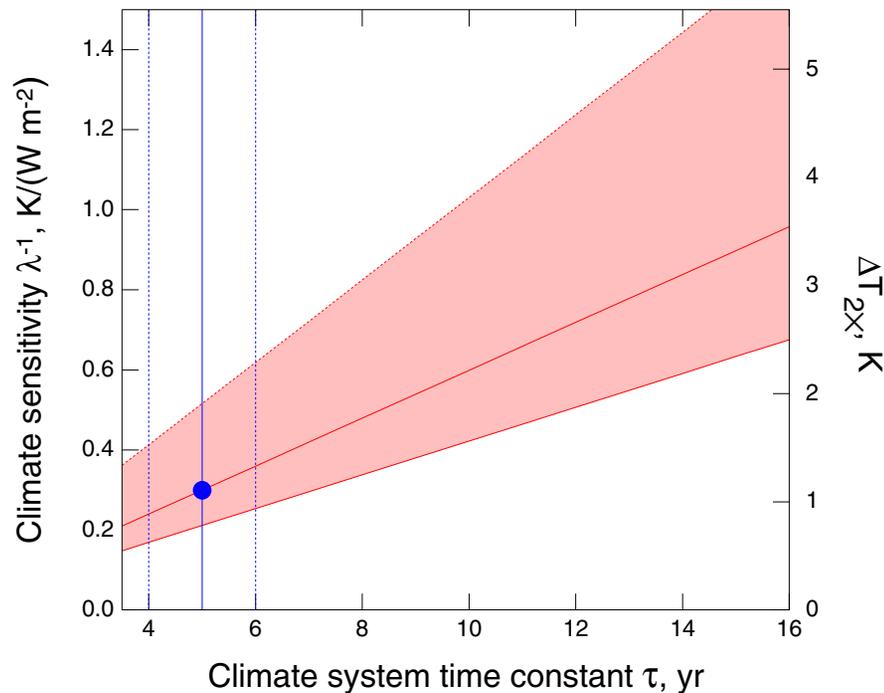
SUMMARY RESULTS

Quantity	Unit	Value
Effective global heat capacity C	$\text{W yr m}^{-2} \text{K}^{-1}$	16.9
Effective climate system time constant τ	yr	5
Equilibrium climate sensitivity $\lambda^{-1} = \tau / C$	$\text{K}/(\text{W m}^{-2})$	0.30
Equilibrium temperature increase for $2 \times \text{CO}_2$, $\Delta T_{2\times}$	K	1.1
Total forcing over the 20 th century, $F_{20} = \Delta T_{20} / \lambda^{-1}$	W m^{-2}	1.9
Forcing in 20 th century other than GHG forcing, $F_{20}^{\text{other}} = F_{20} - F_{20}^{\text{ghg}}$ (<i>mainly aerosols</i>)	W m^{-2}	-0.3
Lag in temperature change, ΔT_{lag}	K	0.03

CLIMATE SENSITIVITY AND INFERRED 20th CENTURY TOTAL AND AEROSOL FORCING

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

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



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.

CONCLUDING OBSERVATIONS

- *Climate sensitivity*, the most important measure of potential future climate change, remains highly uncertain.
- Aerosol forcing and hence total forcing are *not well constrained*.
- The similarity of modeled and observed 20th century temperature records is *better than can be justified*.
- The *heat capacity* of the climate system pertinent to climate change on the multi-decadal time scale corresponds to ocean heat penetration of just 100 meters or so.
- The *time constant* of the climate system pertinent to climate change on the multi-decadal time scale appears to be short, about a decade.
- There is *little incremental heating in the pipeline*.

CONCLUDING OBSERVATIONS

(*cont'd*)

- 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.

