CHILLING CONSIDERATIONS ABOUT GLOBAL WARMING:

GREENHOUSE GASES, AEROSOLS, RADIATIVE FORCING, AND IMPLICATIONS

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QUESTIONS ABOUT CLIMATE CHANGE

Are atmospheric **CO_2** ***and other greenhouse gases*** increasing?
What human or other activities are ***responsible***?

Is Earth's temperature increasing?
Can temperature increase be ***quantitatively understood*** and ***related to causes?***

What ***future temperature increases*** (and other climate changes) can be expected? What is the uncertainty?

What is the ***take-home message*** regarding climate change?

OUTLINE

Radiative fluxes and radiative forcing of climate change

Carbon dioxide increase: sources, mixing ratio, forcing

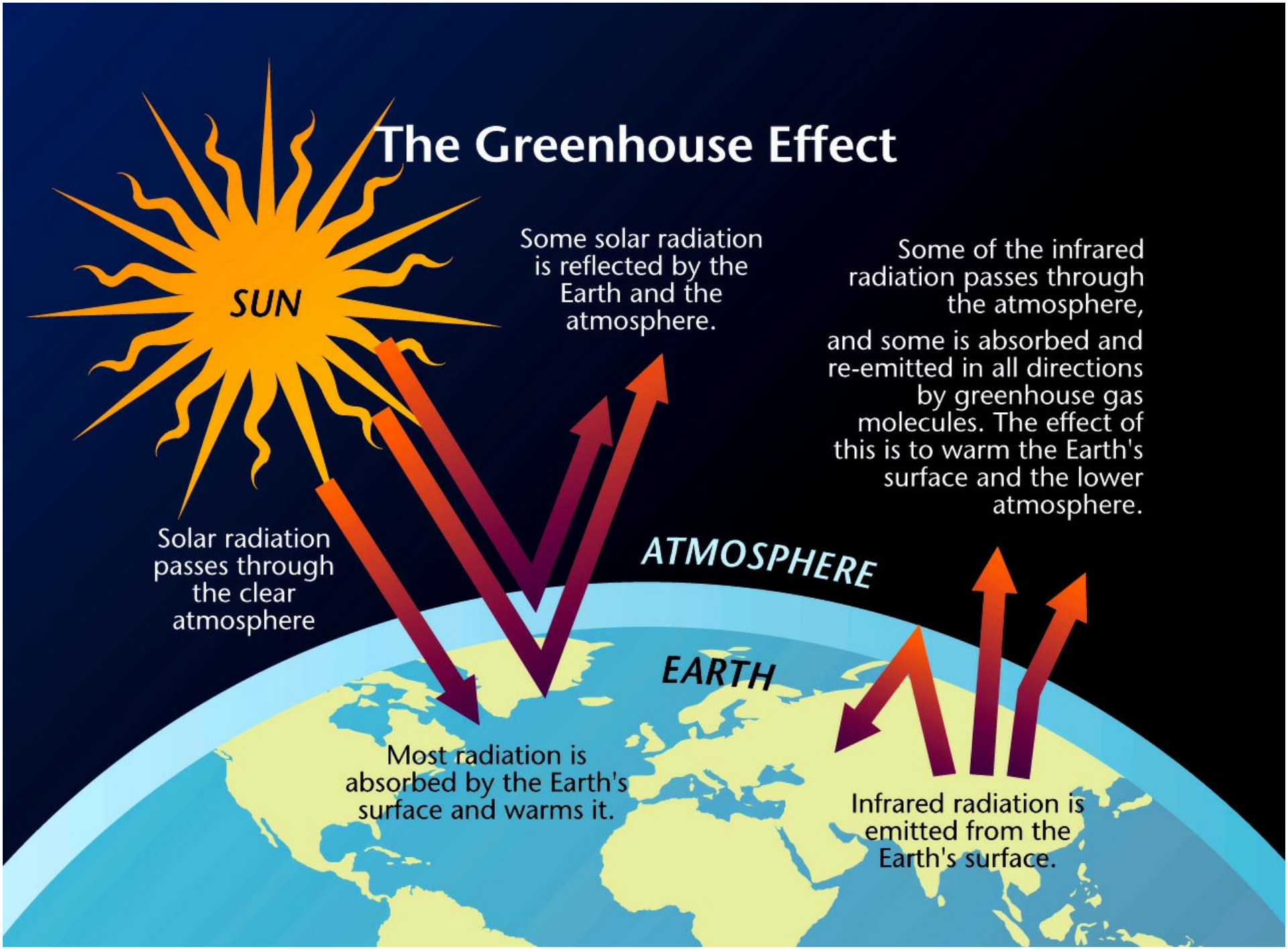
Global temperature change

Climate sensitivity and time constant

Radiative forcing by anthropogenic aerosols

Implications of aerosol forcing

Concluding remarks


The Greenhouse Effect
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
Some of the infrared radiation passes through the atmosphere,
and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation passes through the clear atmosphere
ATMOSPHERE
EARTH
Most radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

ATMOSPHERIC RADIATION

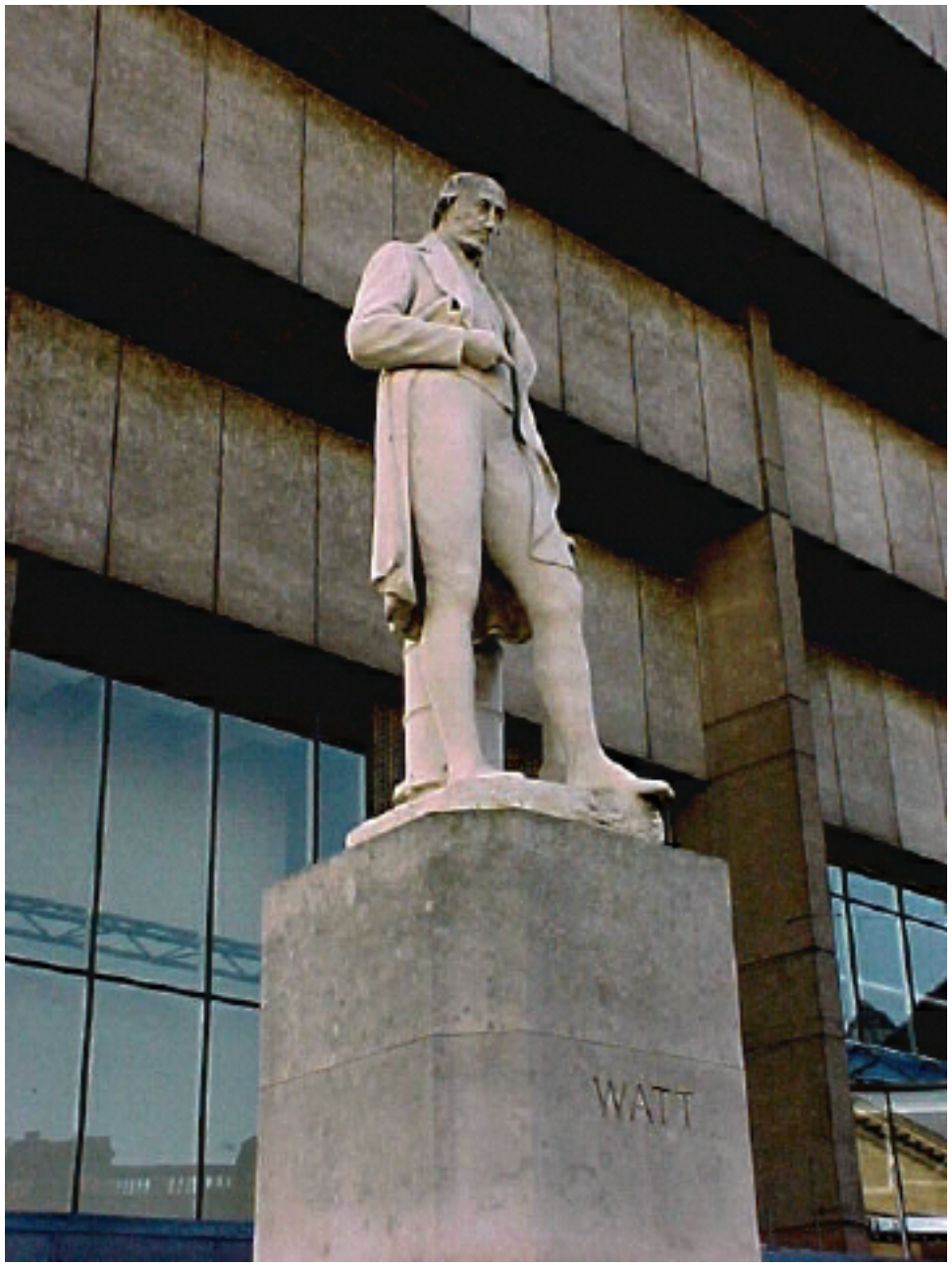
Energy per area per time

Power per area

Unit:

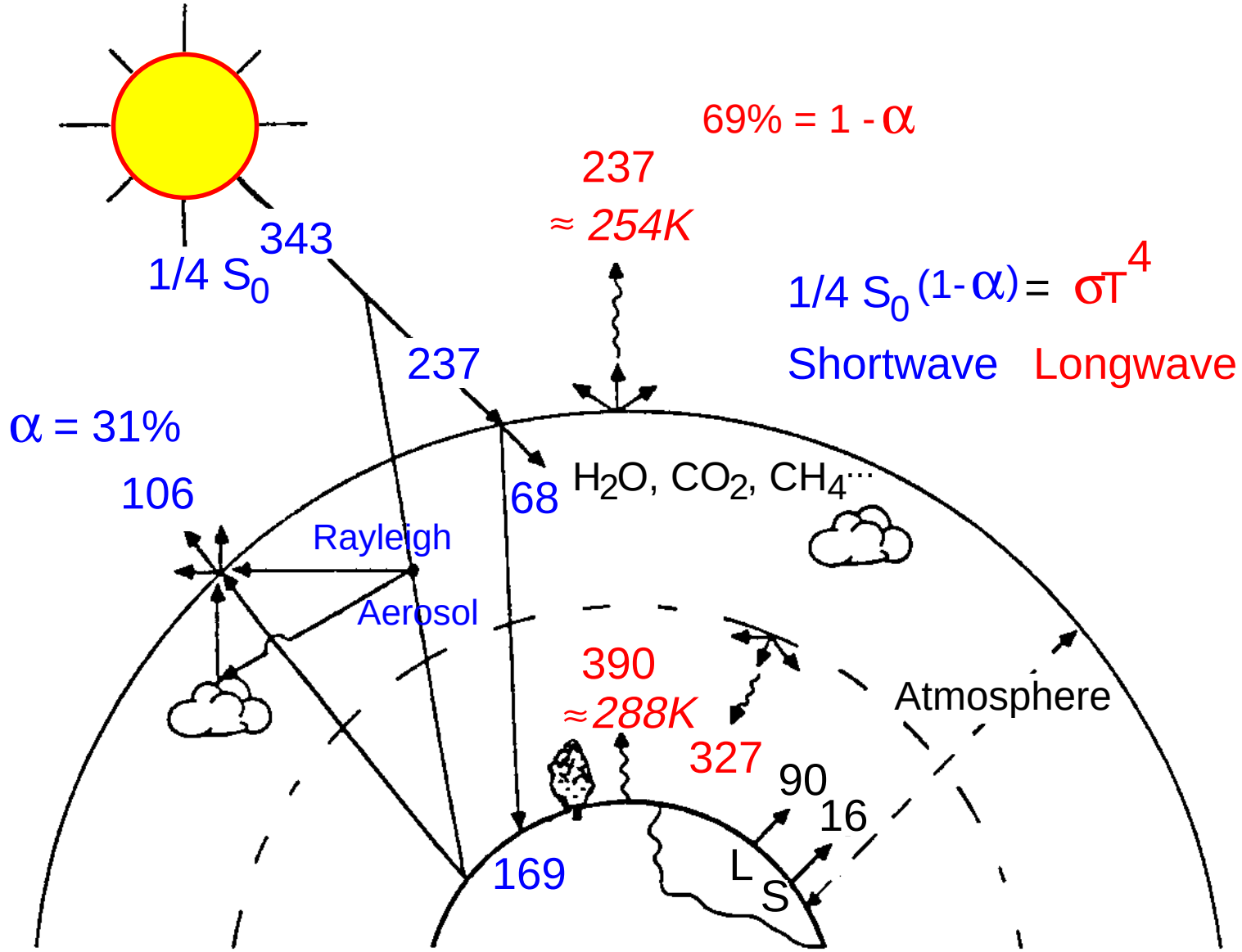
Watt per square meter

$W\ m^{-2}$



GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter

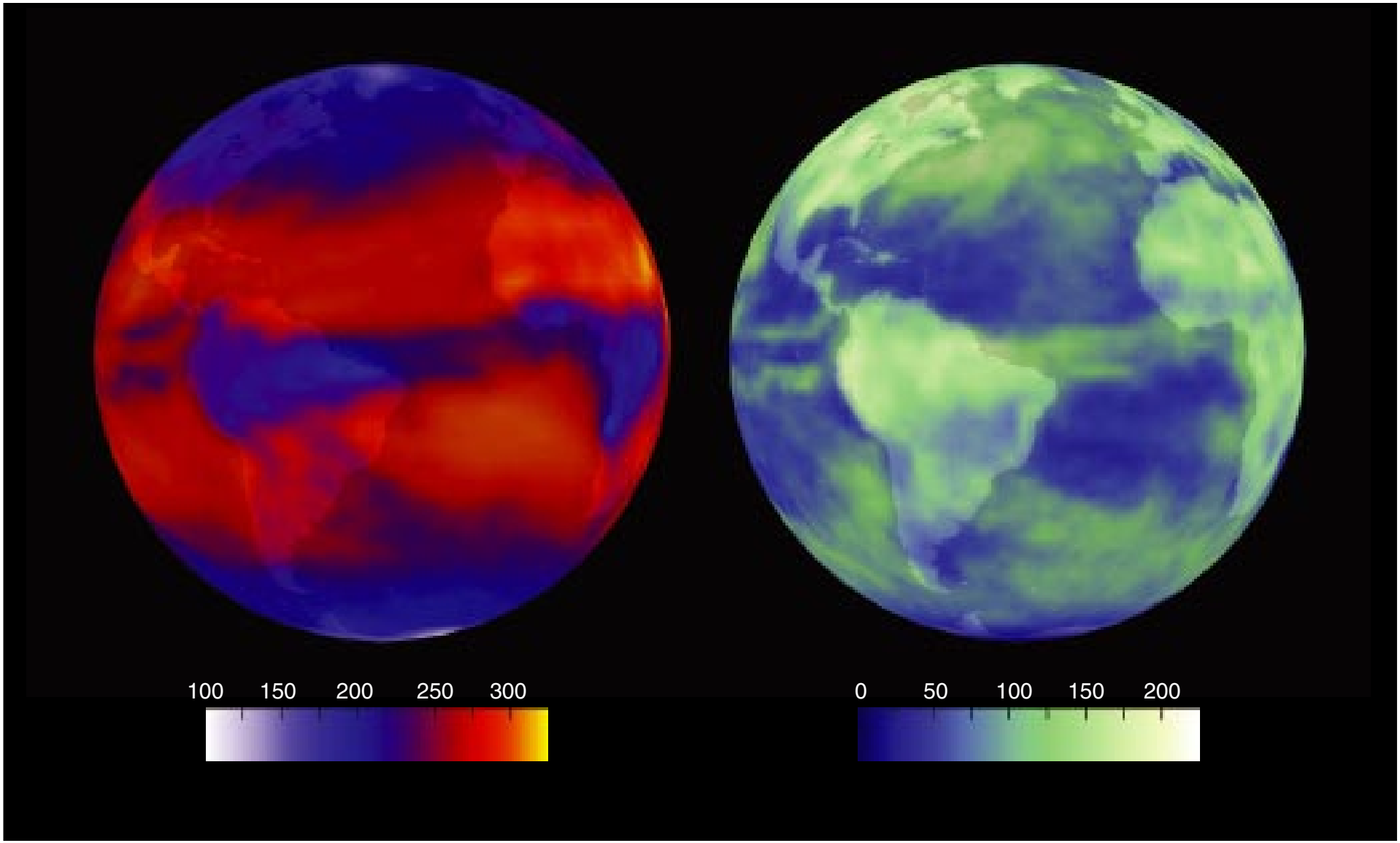


Schwartz, 1996, modified from Ramanathan, 1987

GEOGRAPHICAL VARIATION OF ATMOSPHERIC RADIATION

Annual average radiative flux at top of atmosphere, W m^{-2}

Emitted thermal infrared Reflected shortwave



CERES (Clouds and Earth's Radiant Energy System satellite, March, 2000 - May, 2001

RADIATIVE FORCING OF CLIMATE CHANGE

A ***change*** in a radiative flux term in the Earth's radiation budget, ΔF, W m^{-2}.

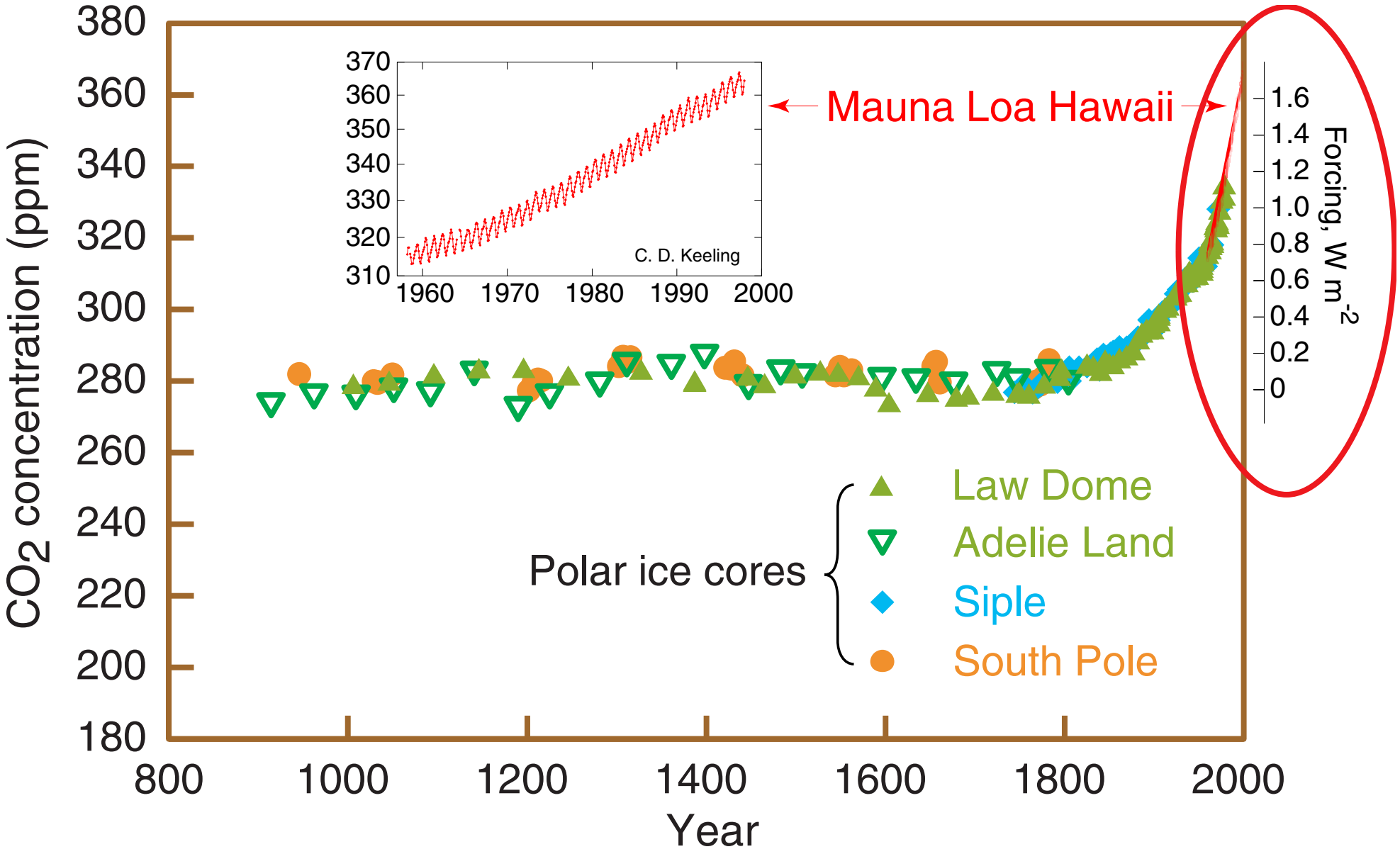
Working hypothesis:

On a global basis radiative forcings are ***additive*** *and* ***fungible***.

The radiative forcing concept underlies much of the assessment of climate change over the industrial period.

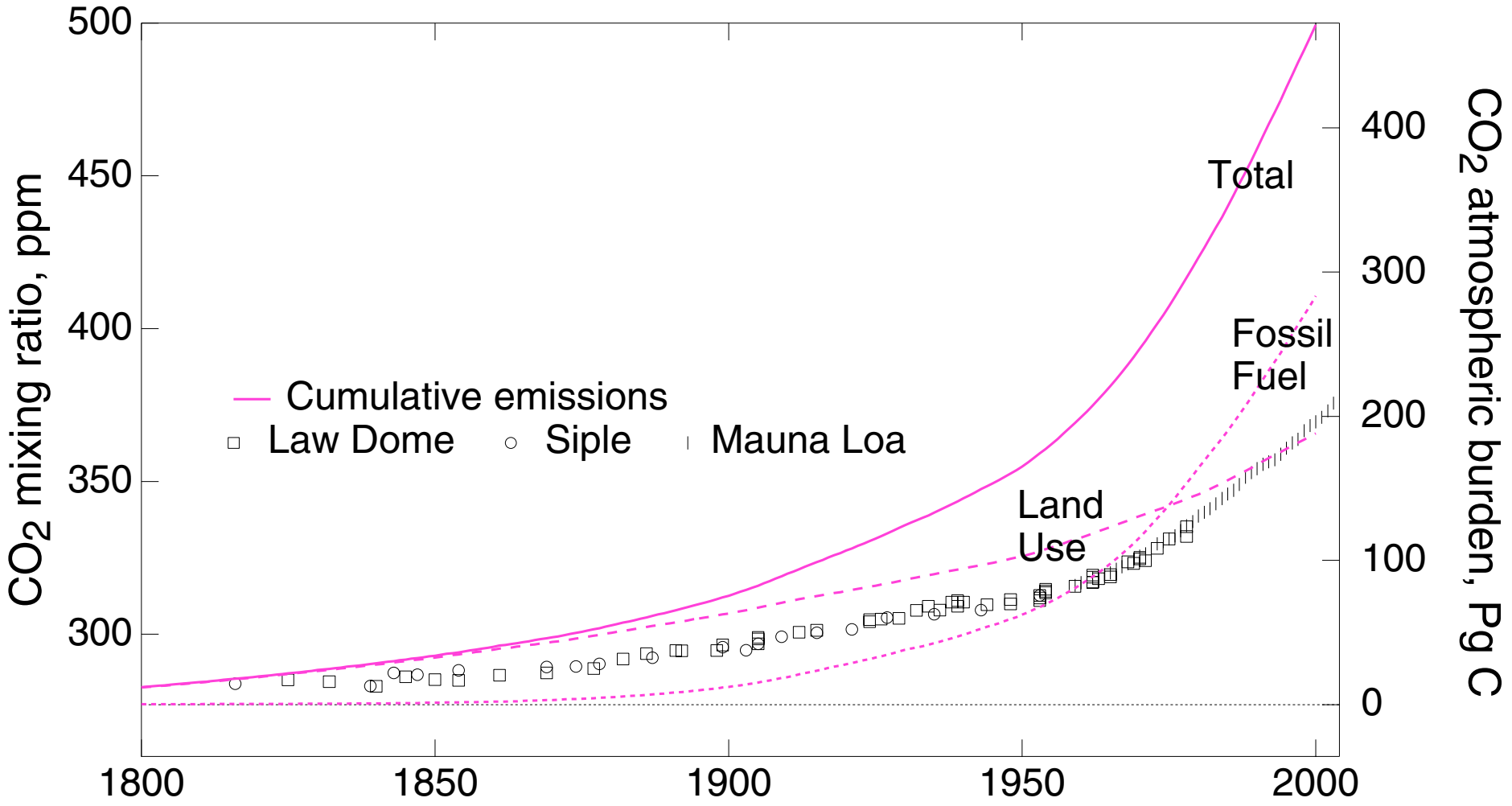
CARBON DIOXIDE INCREASE AND RADIATIVE FORCING

ATMOSPHERIC CARBON DIOXIDE IS INCREASING

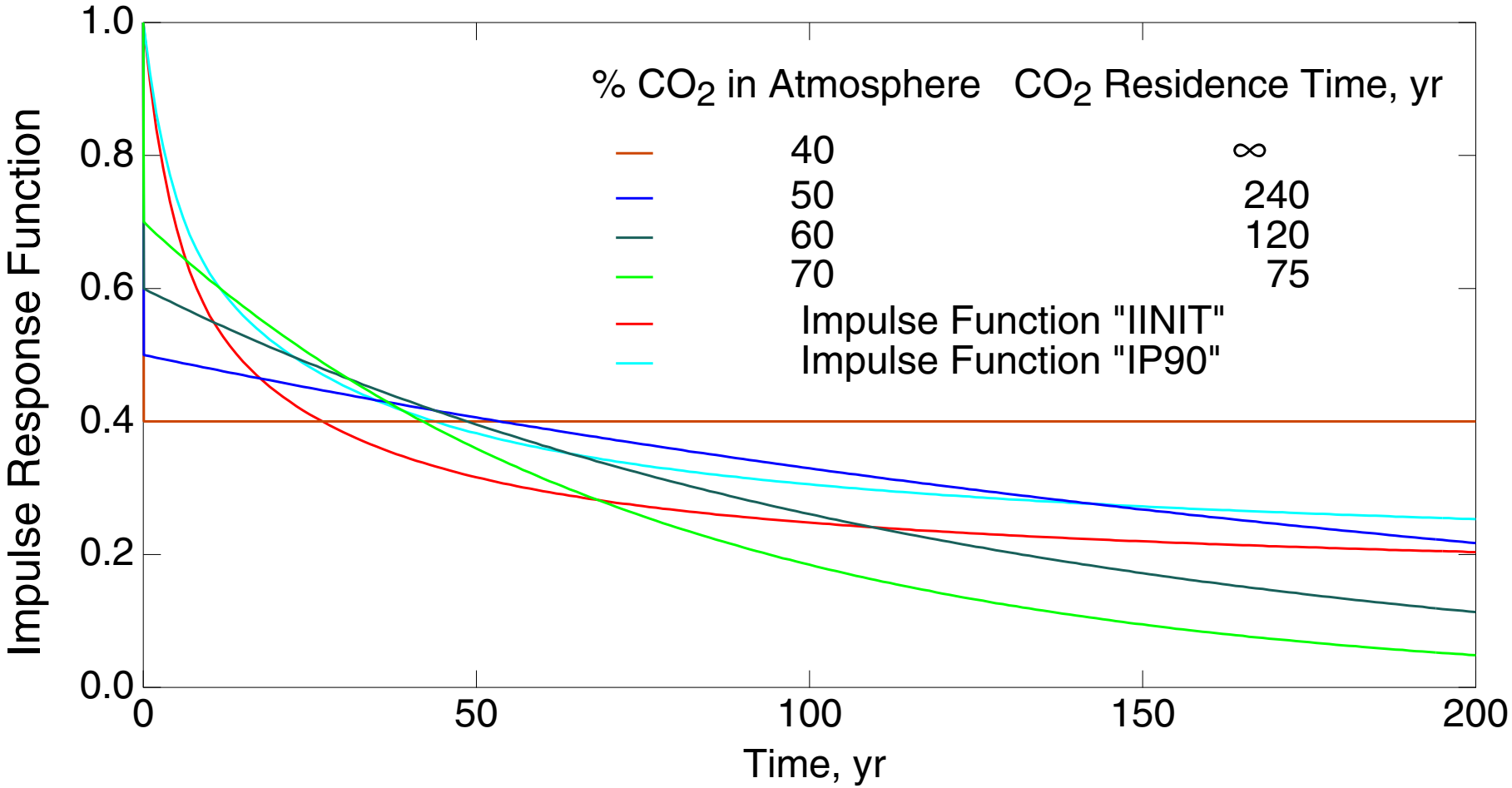


Global carbon dioxide concentration and infrared radiative forcing over the last thousand years

CARBON DIOXIDE MIXING RATIO AND CUMULATIVE EMISSIONS, 1800-2000

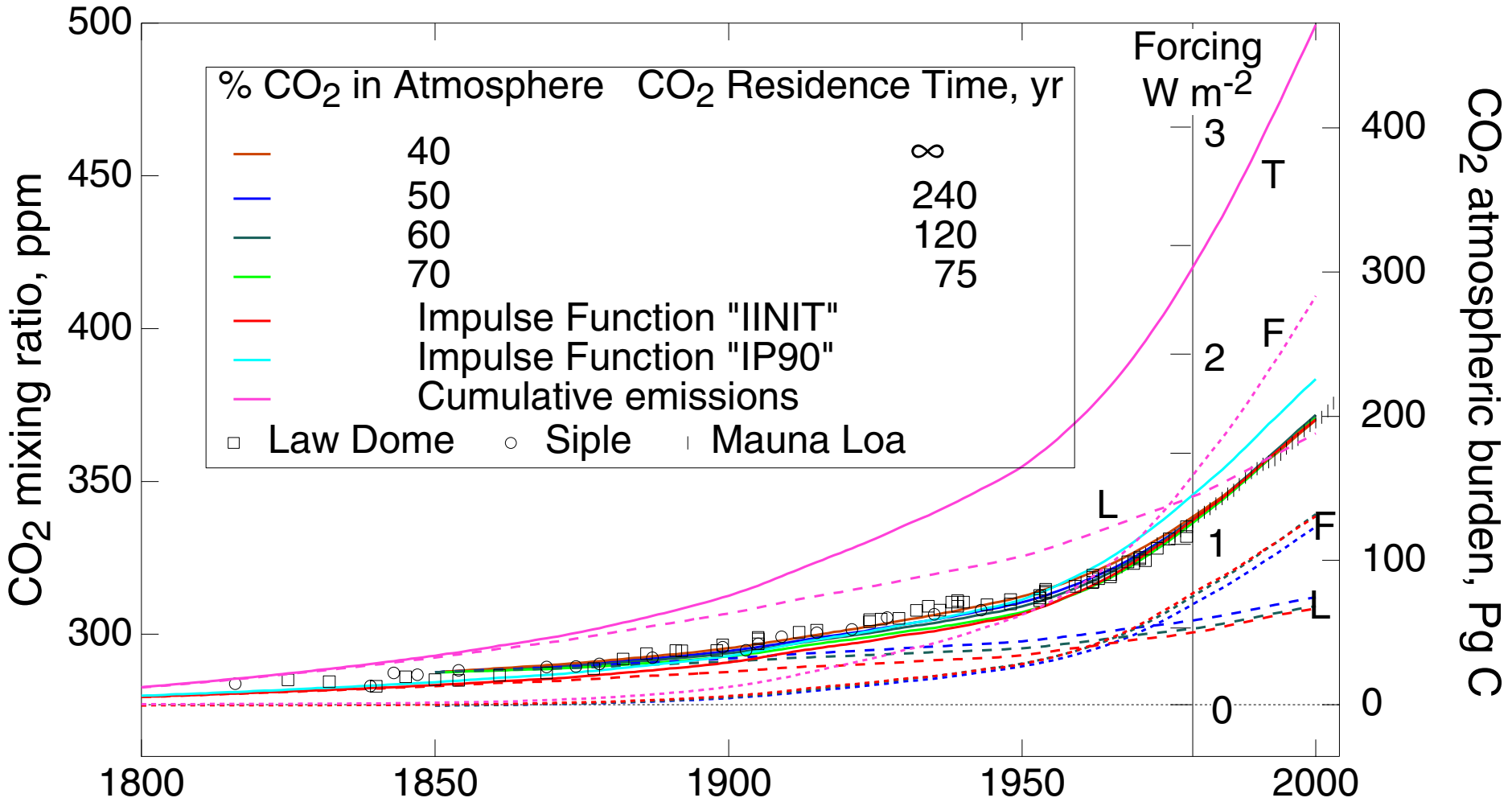


IMPULSE PROFILES FOR ATMOSPHERIC CARBON DIOXIDE



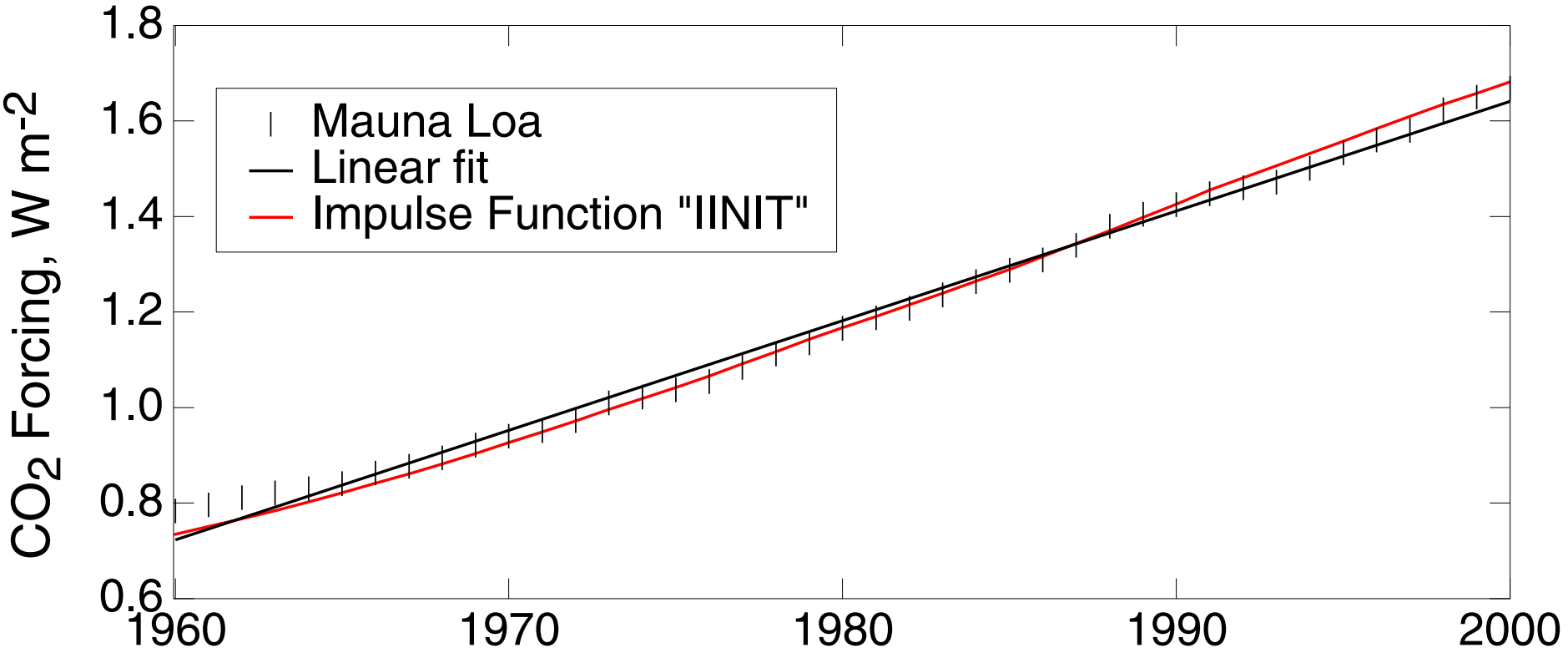
$$[CO_2](t) = [CO_2](0)I(t)$$

CARBON DIOXIDE MIXING RATIO AND RADIATIVE FORCING, 1800-2000



CARBON DIOXIDE FORCING, 1960-2000

$$F_{CO2} = \frac{F_{2\times}}{\ln 2} \ln\left\{\frac{[CO_2]}{[CO_2]_0}\right\} \approx 5.77 \text{ W m}^{-2} \ln\left\{\frac{[CO_2]}{[CO_2]_0}\right\}$$

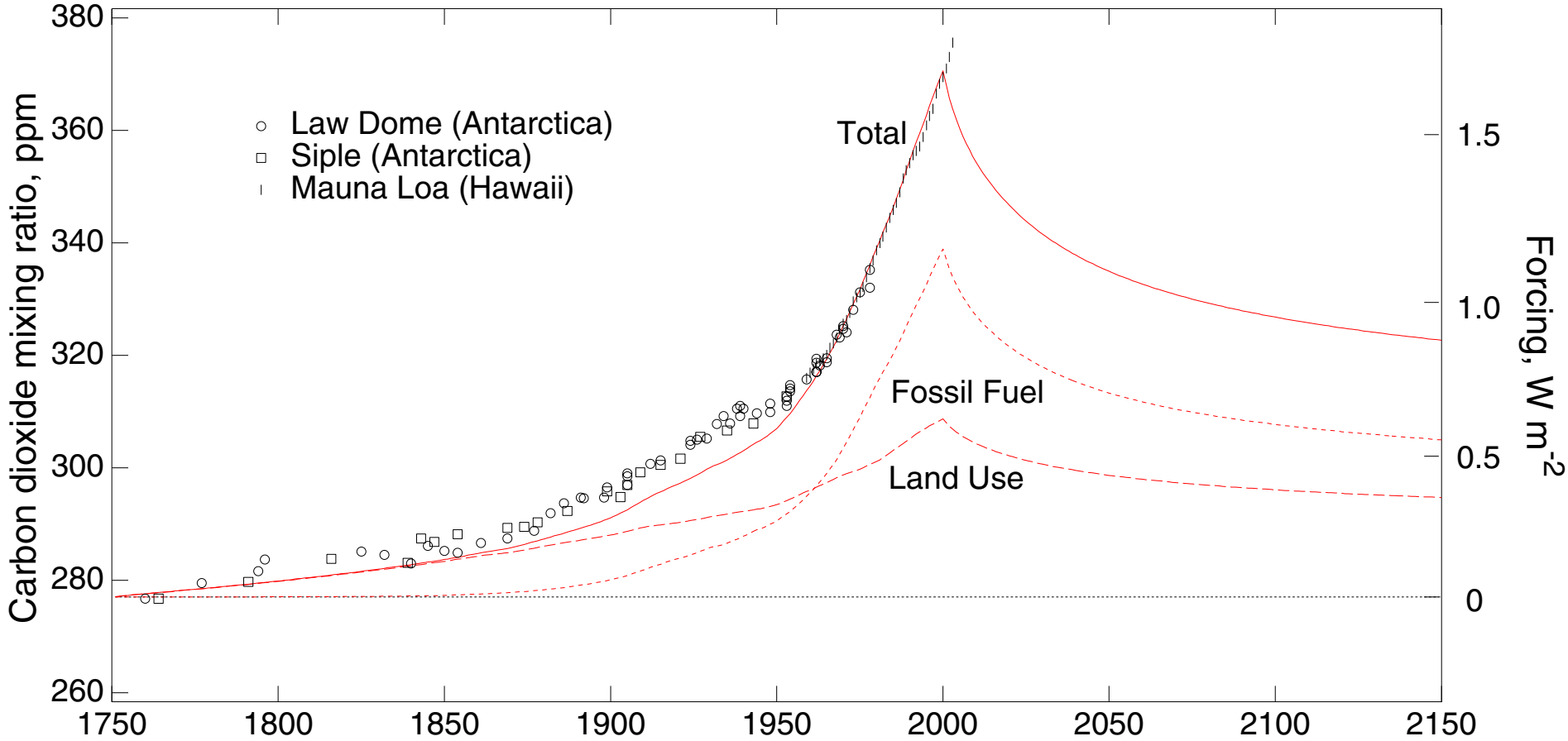


Data: Keeling and Whorf, 2000

$$d\mathit{Forcing}/d\mathit{time} = 0.022 \text{ W m}^{-2} \text{ yr}^{-1}$$

FUTURE ATMOSPHERIC CO_2

Projection of CO_2 ***mixing ratio and forcing*** due to anthropogenic emissions from 1750 to 2000



The footprint of prior CO_2 emissions lasts well beyond a century.

OBSERVATIONS ABOUT CO_2

The residence time of excess atmospheric CO_2 is ~100 years.

CO_2 from ***land use emissions*** was the dominant contribution to excess CO_2 and its climate forcing over the last century.

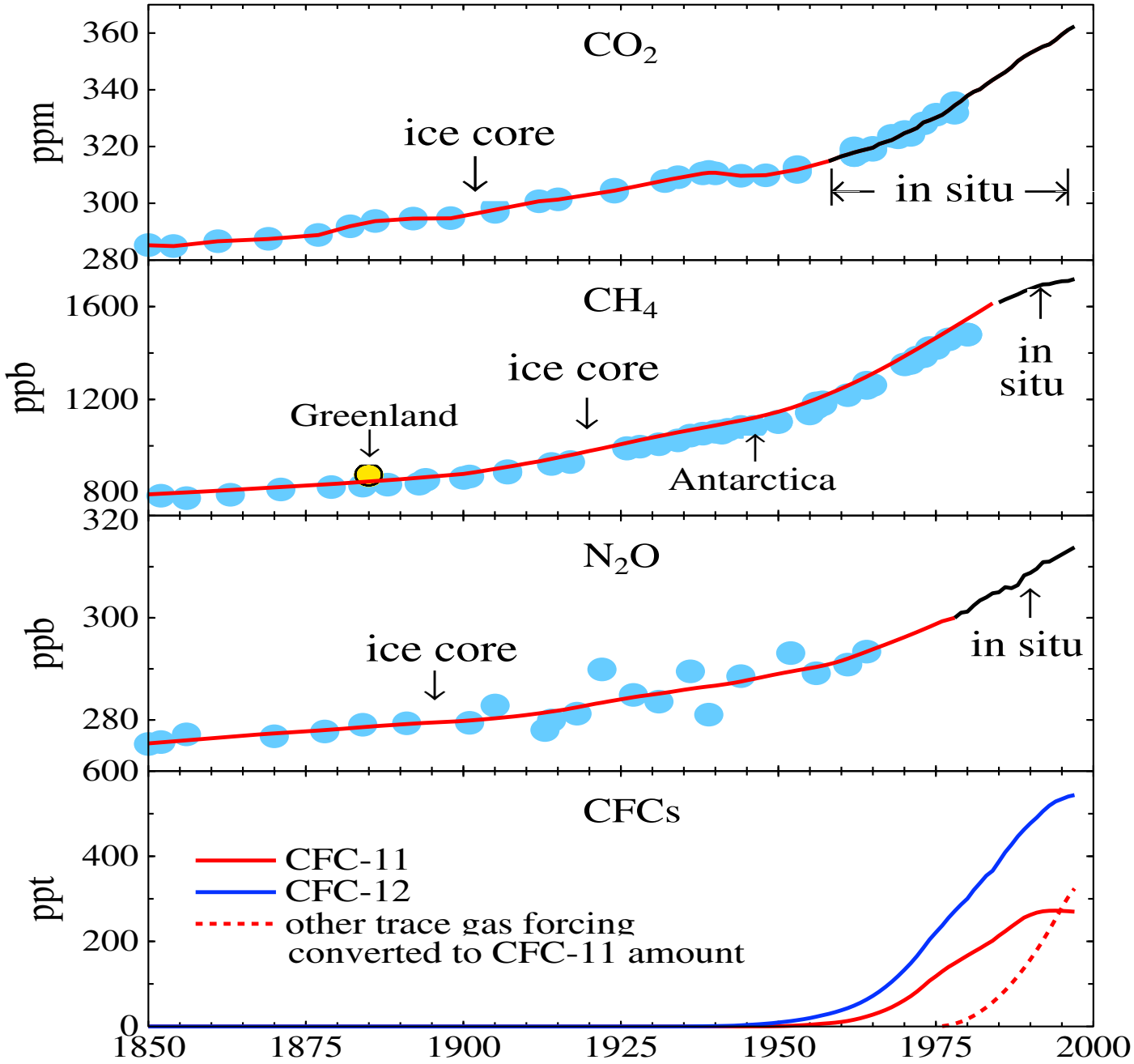
CO_2 from ***fossil fuel combustion*** now the dominant contribution to excess CO_2 and its climate forcing.

Fossil fuel CO_2 emissions are increasing with time constant of ~40 years.

Excess CO_2 now in the atmosphere is ~40 years' emissions.

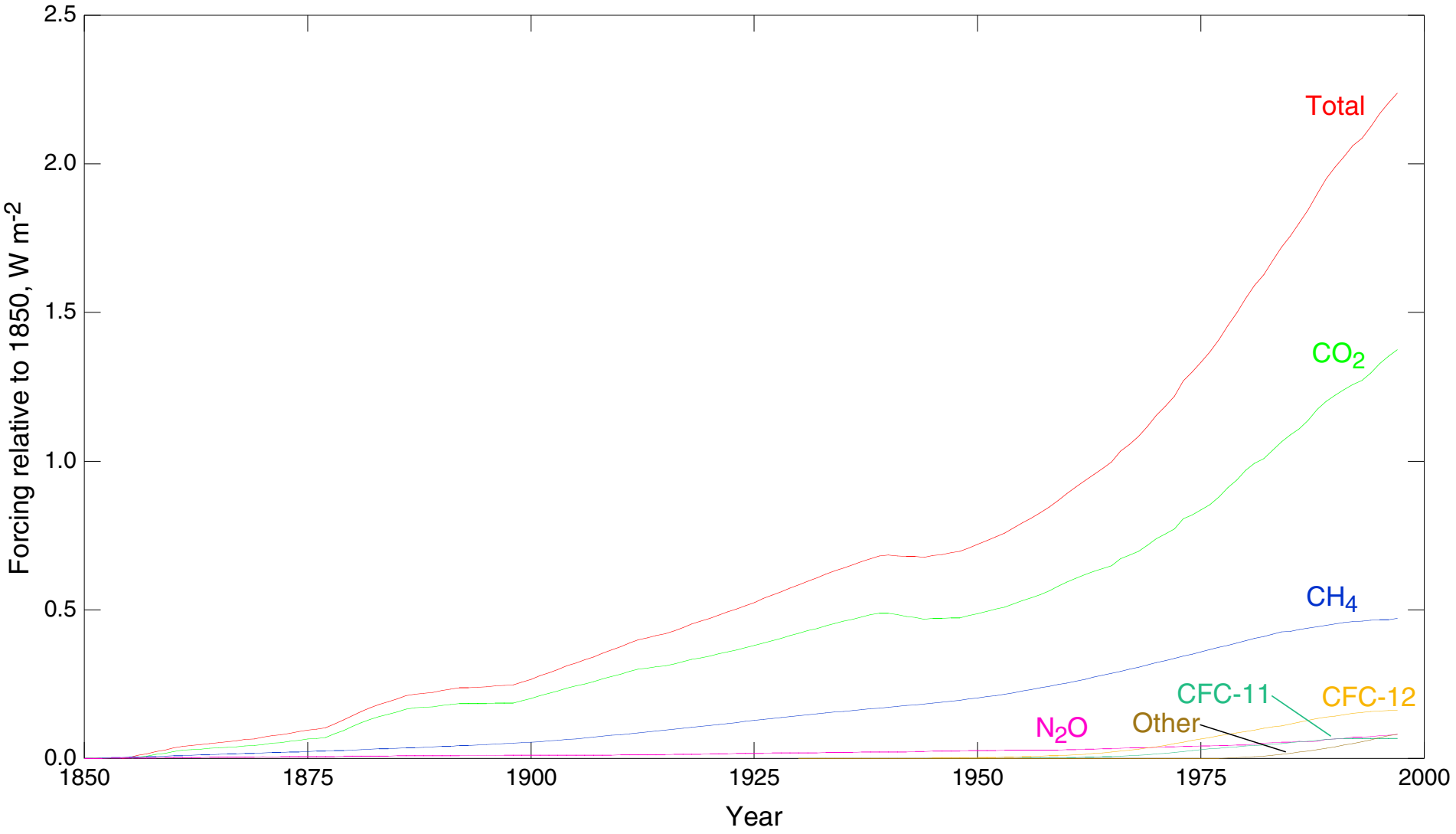
Present excess CO_2 and its forcing will persist for centuries.

GREENHOUSE GAS MIXING RATIOS OVER THE INDUSTRIAL PERIOD



Hansen *et al.*, PNAS. 1998

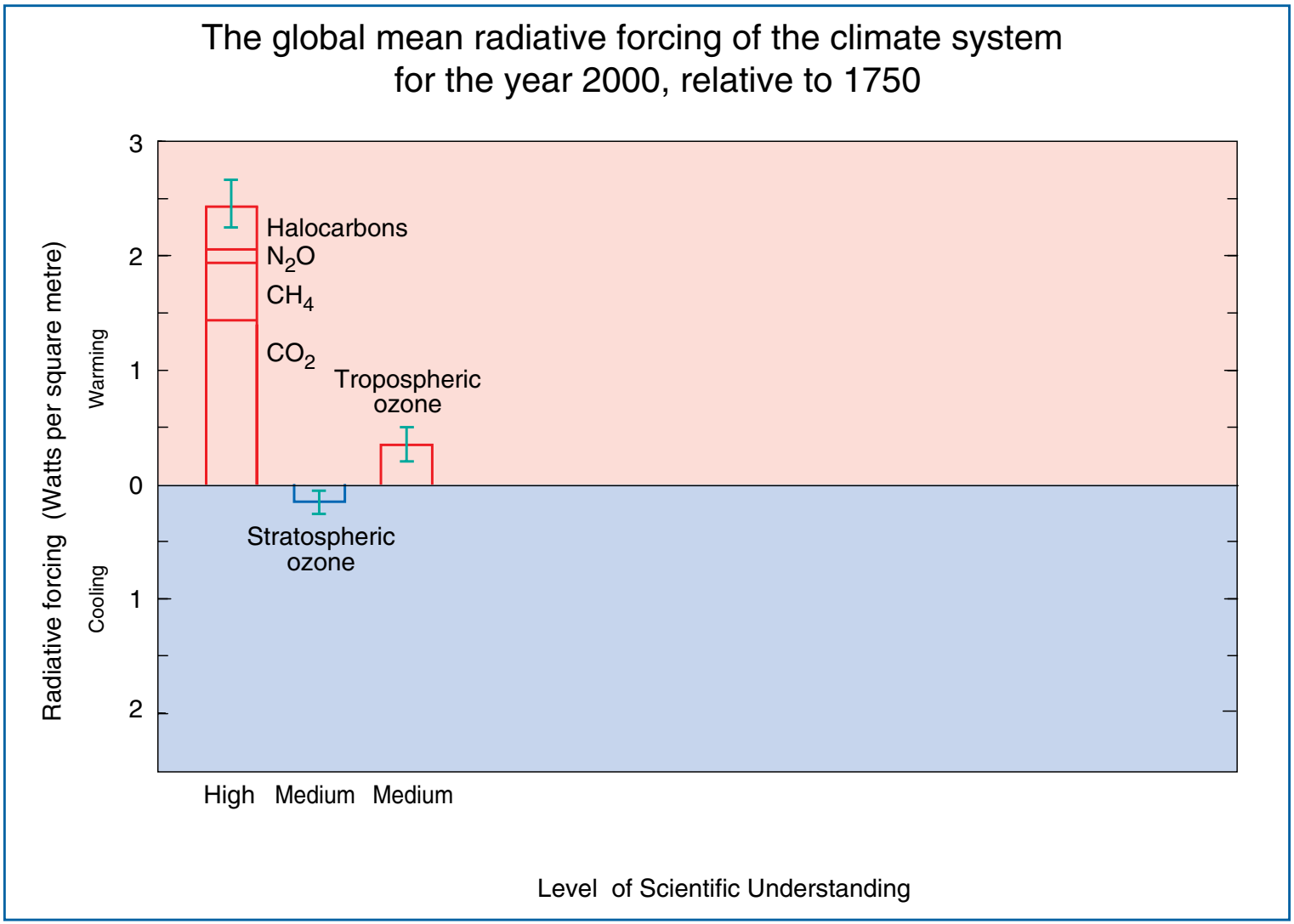
GREENHOUSE GAS FORCINGS OVER THE INDUSTRIAL PERIOD



Data: GISS

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

Greenhouse gases



Summary for Policymakers

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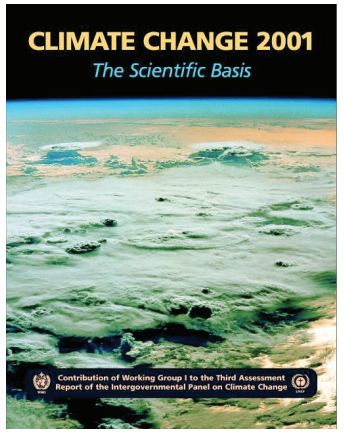
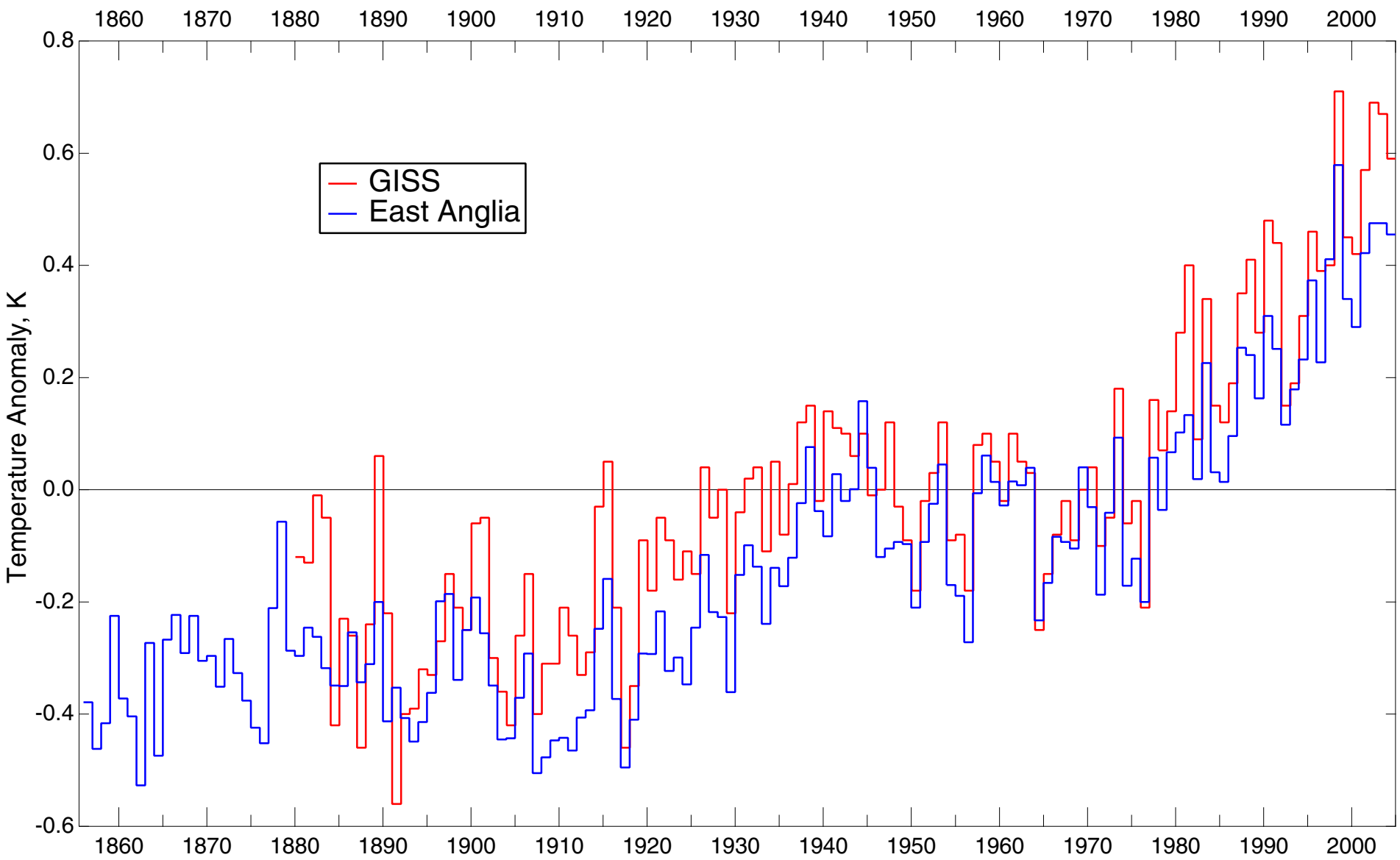
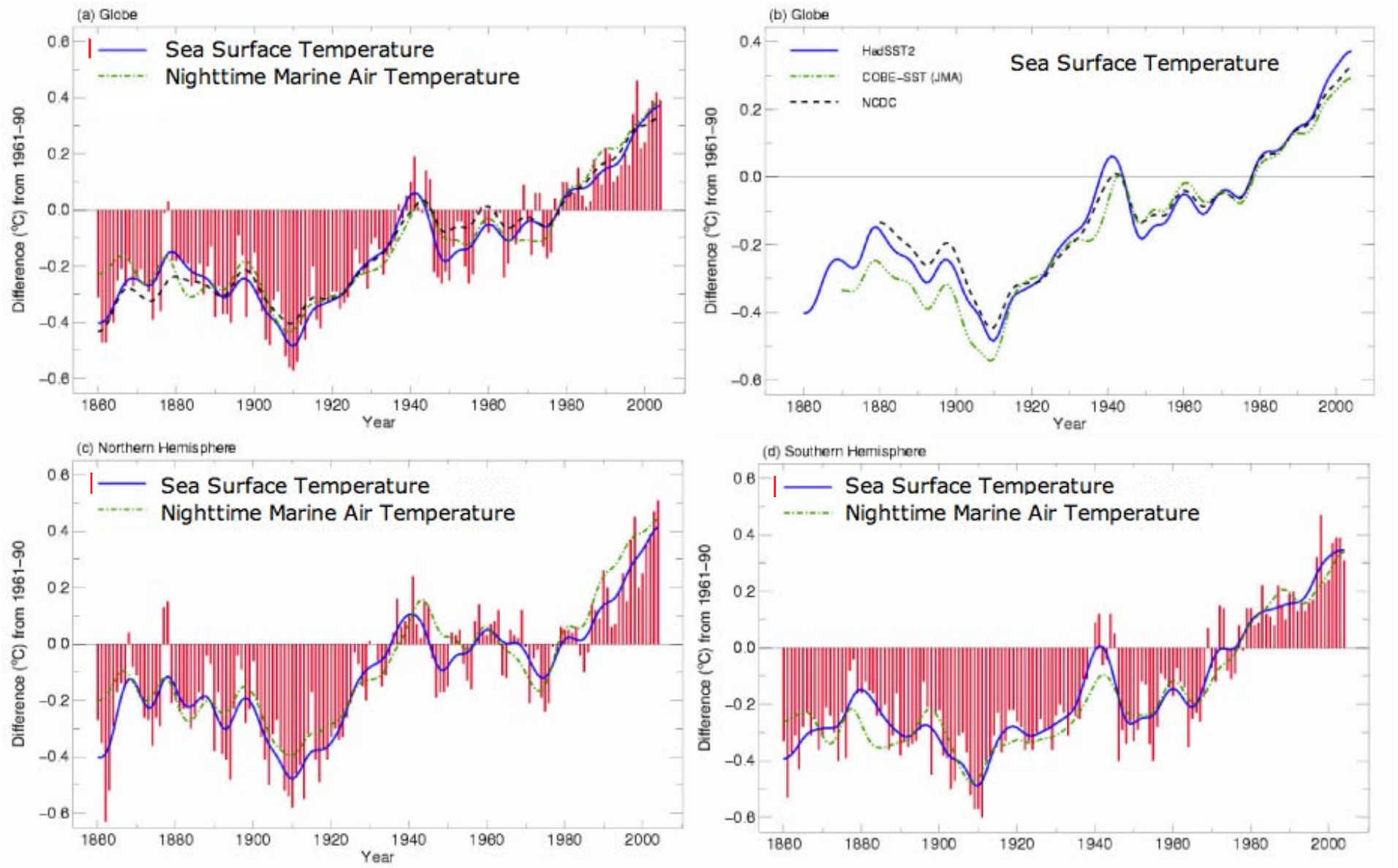


IS EARTH'S TEMPERATURE INCREASING?

GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD

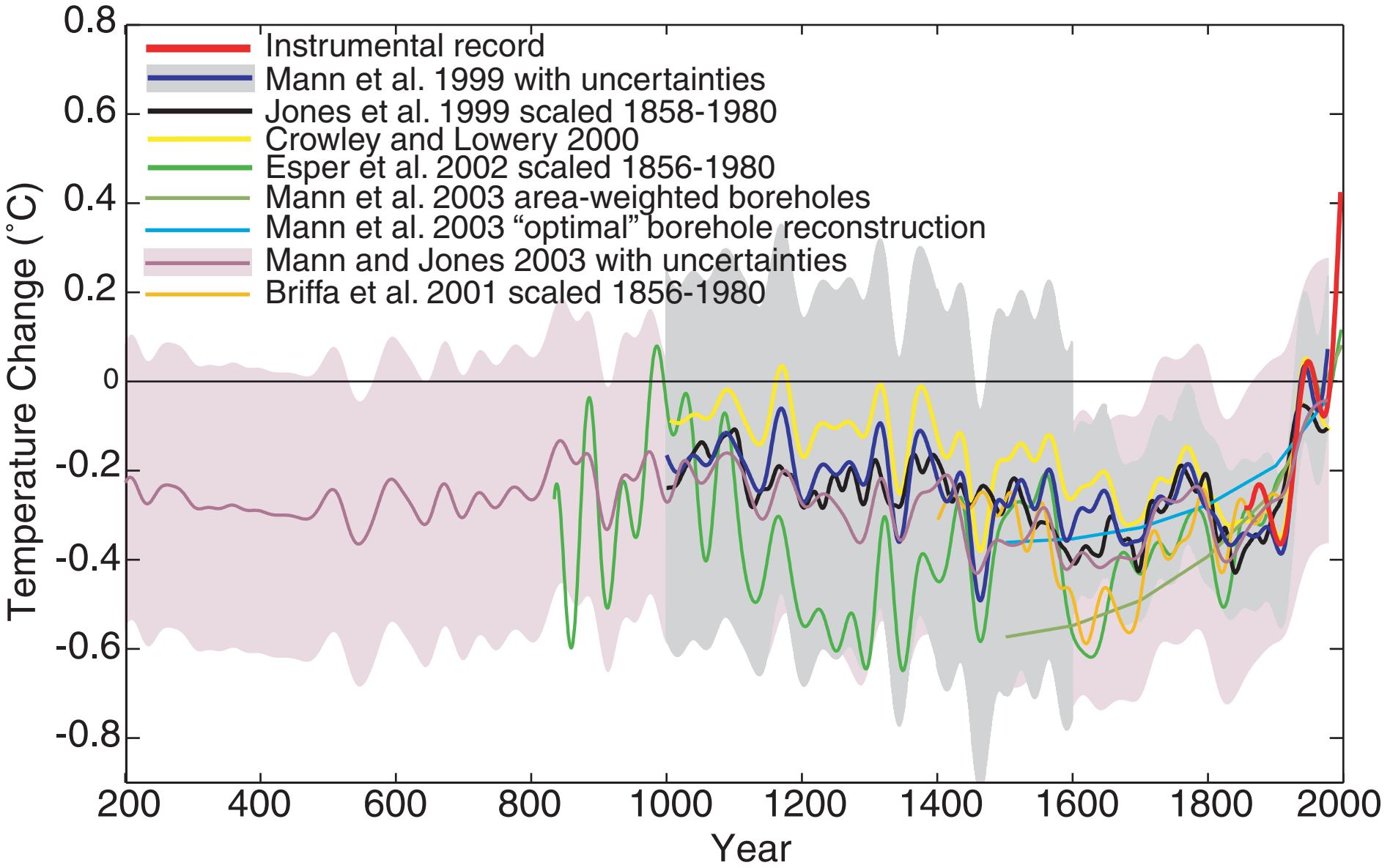


OCEAN SURFACE TEMPERATURE ANOMALY



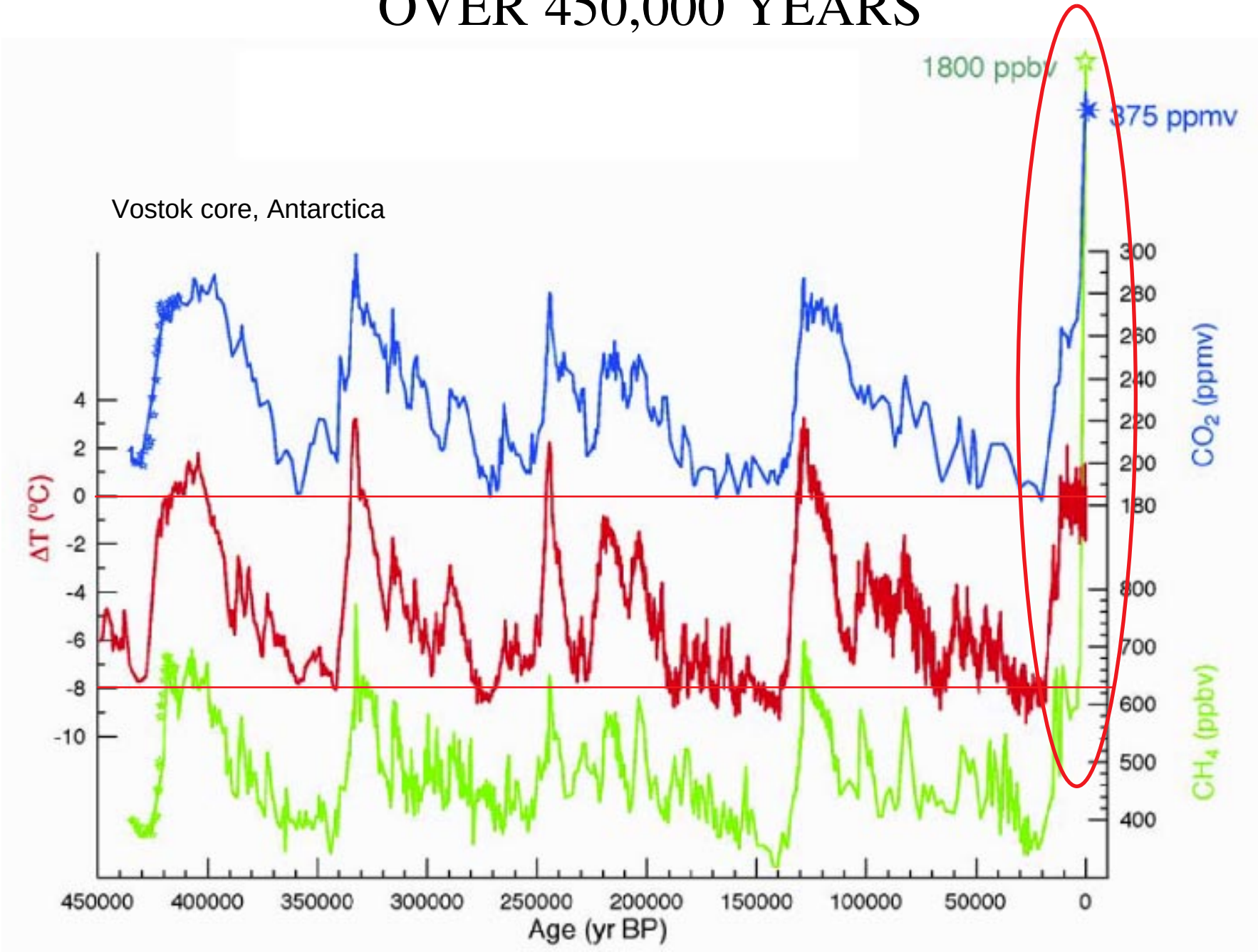
Rayner et al., 2005

NORTHERN HEMISPHERE TEMPERATURE OVER 2000 YEARS



Modified from Mann et al., Eos, 2003

GREENHOUSE GASES AND TEMPERATURE OVER 450,000 YEARS



Modified from Petit et al., Nature, 1999

Prediction is difficult,
especially about the future.

– Niels Bohr

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 depends on the magnitude of the forcing, not its nature or its spatial distribution.

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

CLIMATE SENSITIVITY

The ***change*** in global and annual mean temperature per unit forcing, λ^{-1}, K/(W m^{-2}).

TOP-LEVEL QUESTION IN CLIMATE CHANGE SCIENCE

- ***How much will the global mean temperature change?***

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

where F is the ***forcing*** and λ^{-1} is the ***climate sensitivity***.

- A ***forcing*** is a change in a radiative flux component, W m^{-2}.
- Forcings are thought to be ***additive*** and ***fungible***.

- ***What is Earth's climate sensitivity?***
  - ***U.S. National Academy Report (Charney, 1979):*** F = 4 W m^{-2}

> "We estimate the most probable global warming for a doubling of CO_2 to be ***near 3 degrees C***, with a probable error of ***plus or minus 1.5 degrees***.

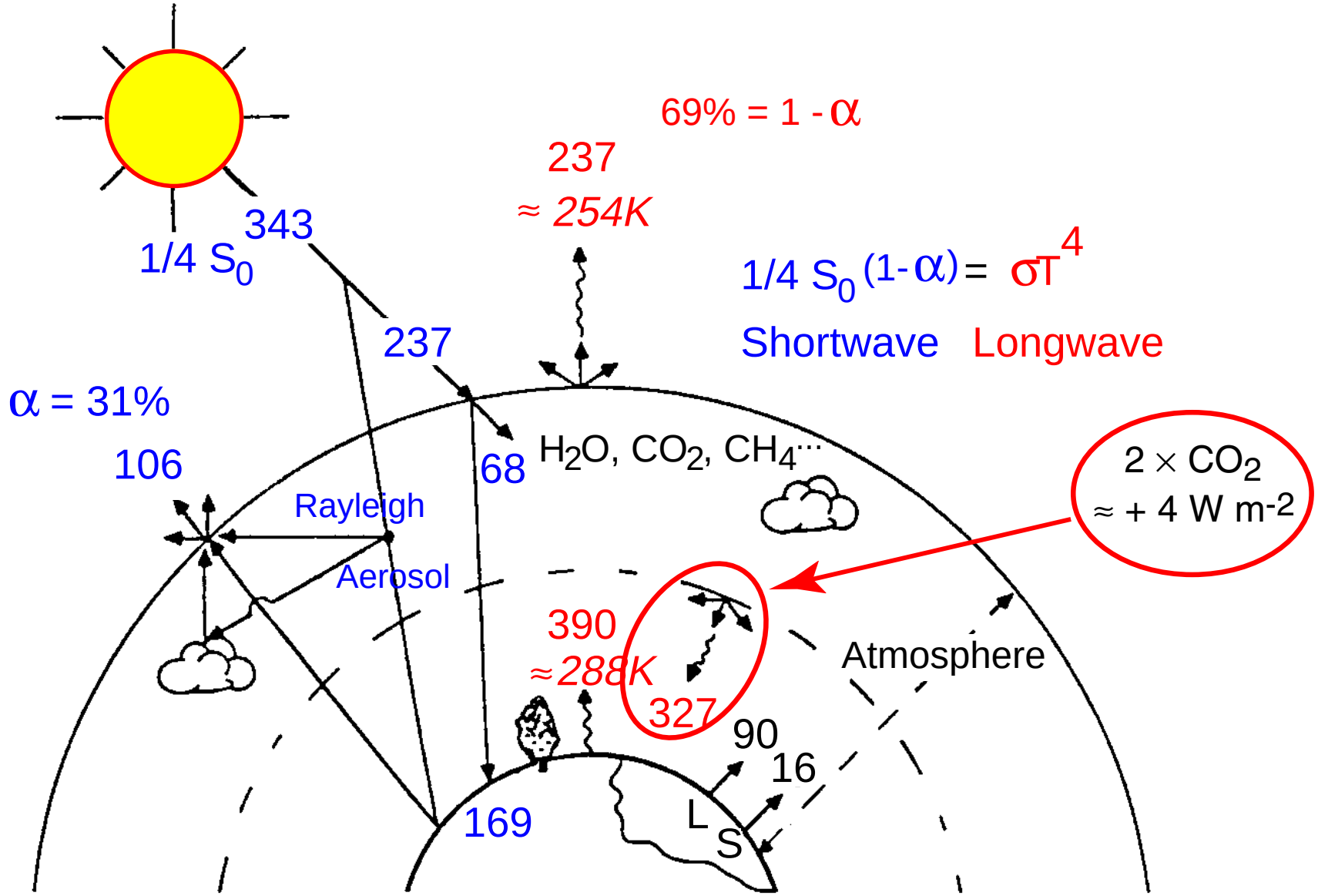
  - ***Intergovernmental Panel on Climate Change (IPCC, 2001):***

> "Climate sensitivity [to CO_2 doubling] is likely to be in the range ***1.5 to 4.5˚C***.

This level of uncertainty is not very useful for policy planning.

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

HOW CAN CLIMATE SENSITIVITY BE DETERMINED?

Climate sensitivity $\lambda^{-1} = \Delta T \,/\, F$

- ***Climate models*** evaluated by performance on prior climate change, and/or

- ***Empirical determination*** from prior climate change.

- Either way, ΔT and F must be determined with sufficiently small uncertainty to yield an uncertainty in λ^{-1} that is useful for informed decision making.

CLIMATE SYSTEM RESPONSE TO FORCING

TIME CONSTANTS OF EARTH'S CLIMATE SYSTEM

Consider a perturbation to the climate system

How long does it take for the system to adjust to the new state?

There are many time constants:

Minutes. It gets cooler when the sun goes "behind a cloud."

Hours. It is cooler at night than during the day; but there is a lag.

Months. It is colder in winter than in summer, but there is a lag.

Years. Thermal buffering of the ocean mixed layer.

Thousands of years. The deep oceans.

Millions of years. Thermal mass of the whole planet (Kelvin and the age of Earth)

RATE OF GLOBAL HEATING DUE TO ENERGY IMBALANCE

Global energy balance: $\frac{dH}{dt} = Q - E$

Q is absorbed solar energy E is emitted longwave flux

Global mean temperature: $\frac{dT}{dt} = \frac{Q - E}{C}$

C is pertinent heat capacity $C = f_{\mathrm{w}} c_{\mathrm{w}} \rho_{\mathrm{w}} z_{\mathrm{m}} = 9.4$ W yr m^{-2} K^{-1}

f_{w} = fraction of Earth covered by oceans, 0.71

c_{w} = specific heat of water

ρ_{w} = density of water

z_{m} = depth of mixed ocean layer, 100 m

For energy imbalance $Q - E = 1$ W m^{-2}, $dT / dt = 0.1$ K yr^{-1}.

BILLIARD BALL TEMPERATURE SENSITIVITY AND TIME CONSTANT

Evaluated according to the Stefan-Boltzmann radiation law

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

Initially $Q_0 = \sigma T_0^4$

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

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

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

BILLIARD BALL TEMPERATURE SENSITIVITY AND TIME CONSTANT

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

For ocean fraction 0.71 and mixed layer depth 100 m

Climate time constant $\tau_{S\text{-}B} = 2.5$ yr.

This is a very forgiving result!

GLOBAL TEMPERATURE SENSITIVITY AND TIME CONSTANT INCLUDING FEEDBACKS

Global energy balance: $C\frac{dT}{dt} = Q - E = \gamma J_S - \varepsilon\sigma T^4$

$$\Delta\gamma = \frac{d\gamma}{dT}\Delta T \text{ and } \Delta\varepsilon = \frac{d\varepsilon}{dT}\Delta T$$

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

$$\lambda^{-1} = f\frac{T_0}{4\gamma_0 J_S} \text{ where } f = \left(1 - \frac{1}{4}\frac{d\ln\gamma}{d\ln T}\bigg|_0 + \frac{1}{4}\frac{d\ln\varepsilon}{d\ln T}\bigg|_0\right)^{-1}$$

f is denoted the "feedback factor."

$$\tau = C\lambda^{-1} \text{ as before.}$$

TEMPERATURE RESPONSE TO LINEARLY INCREASING FORCING

$$C\frac{dT}{dt} = \beta t + \gamma J_S - \varepsilon\sigma T^4 \qquad \beta = d\text{forcing}/d\text{time}$$

$$\Delta T(t) = \beta\lambda^{-1}[(t-\tau)+\tau e^{-t/\tau}] \text{ and } \Delta H(t) = C\Delta T(t) = \beta\tau[(t-\tau)+\tau e^{-t/\tau}]$$

(λ^{-1} and τ are the same as before; $\tau = C\lambda^{-1}$)

Whence: $$\frac{dH\,/\,dt}{dT\,/\,dt} = \frac{\tau}{\lambda^{-1}} = C$$

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

Whence: $$\lambda^{-1} = \frac{1}{\beta}\frac{dT}{dt}$$ and $$\tau = \frac{1}{\beta}\frac{dH}{dt}$$

EVALUATION OF CLIMATE SYSTEM SENSITIVITY AND TIME CONSTANT

$$\text{Recall } \lambda^{-1} = \frac{1}{\beta}\frac{dT}{dt} \text{ and } \tau = \frac{1}{\beta}\frac{dH}{dt}.$$

Forcing increase rate (CO_2 plus methane): $\beta = 0.0284$ W m^{-2} yr^{-1}.

For $dT/dt = 0.014$ K yr^{-1} $\quad \lambda^{-1} = 0.49$ K/(W m^{-2}); $\quad \Delta T_{2\times} = 2$ K

For $dH/dt = 0.13 \pm 0.05$ W m^{-2} $\quad \tau = 4.6 \pm 1.8$ yr.

This sensitivity is consistent with current understanding.

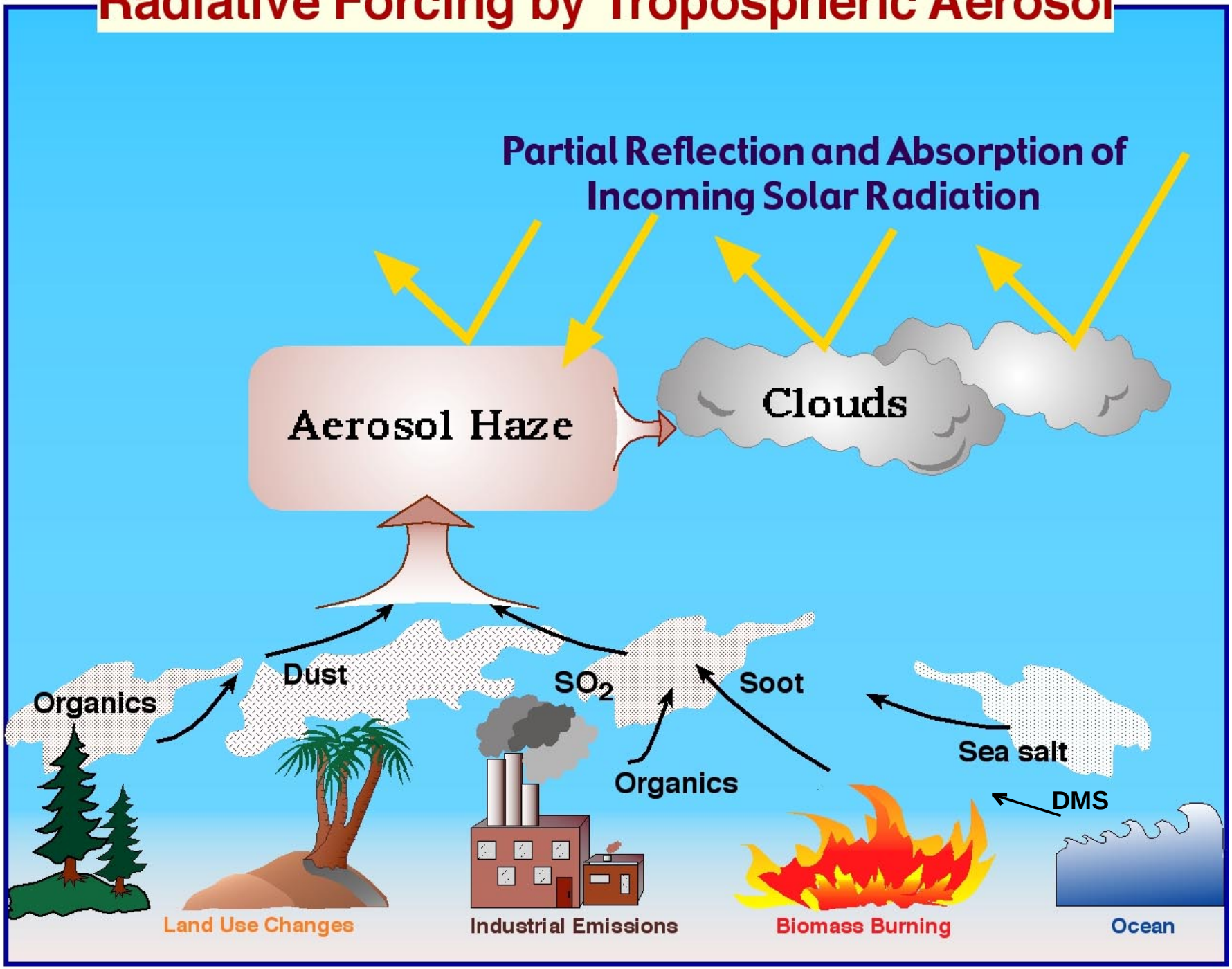
But there are compelling indications that these results may be very misleading.

WHAT'S MISSING FROM THIS STORY?

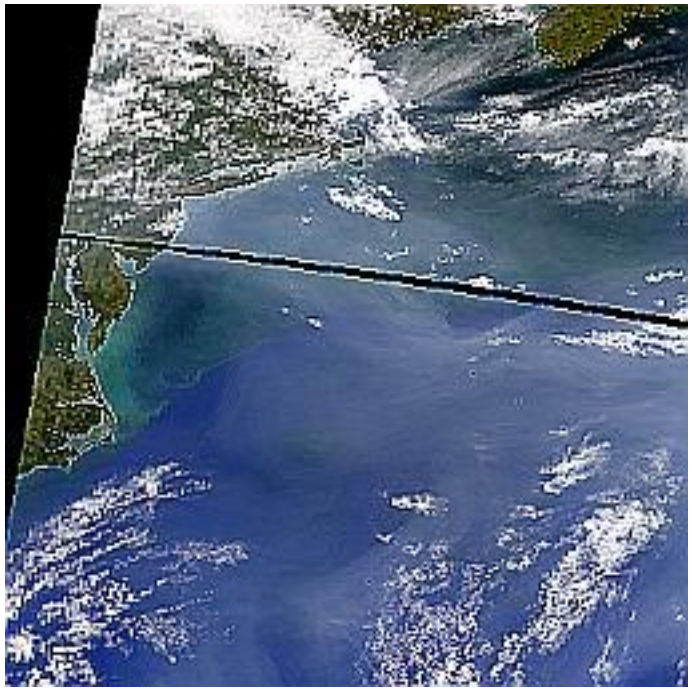
WHAT'S MISSING FROM THIS STORY?

RADIATIVE FORCING BY AEROSOLS

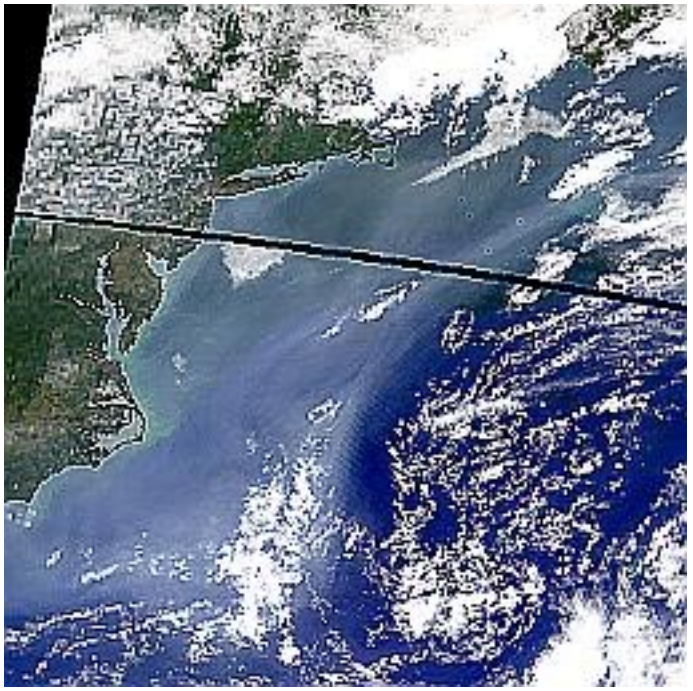
Radiative Forcing by Tropospheric Aerosol



LIGHT SCATTERING BY ANTHROPOGENIC AEROSOLS, 2000

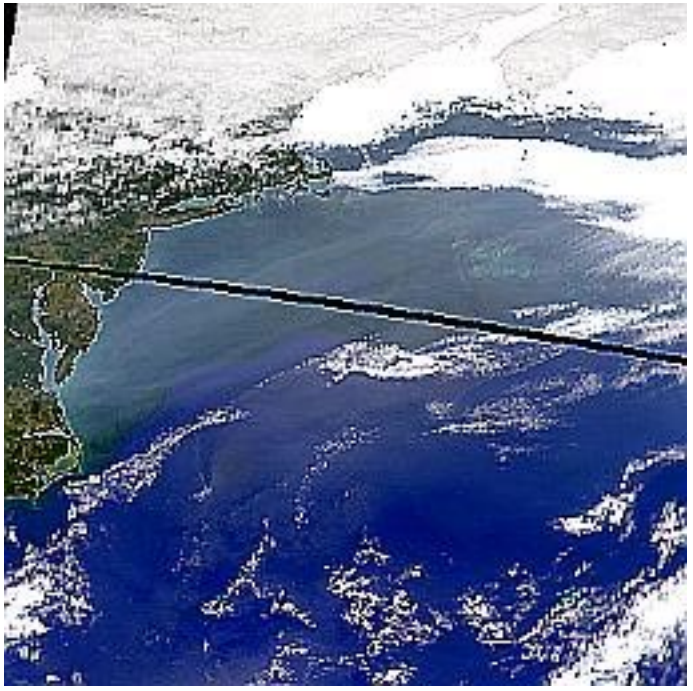


May 8



June 2

June 3



June 11

SEAWIFS images

AEROSOL INFLUENCES ON RADIATION BUDGET AND CLIMATE

Direct Effect (Cloud-free sky)

Light scattering -- Cooling influence

Light absorption -- Warming influence, depending on surface

Indirect Effects (Aerosols influence cloud properties)

More droplets -- Brighter clouds (Twomey)

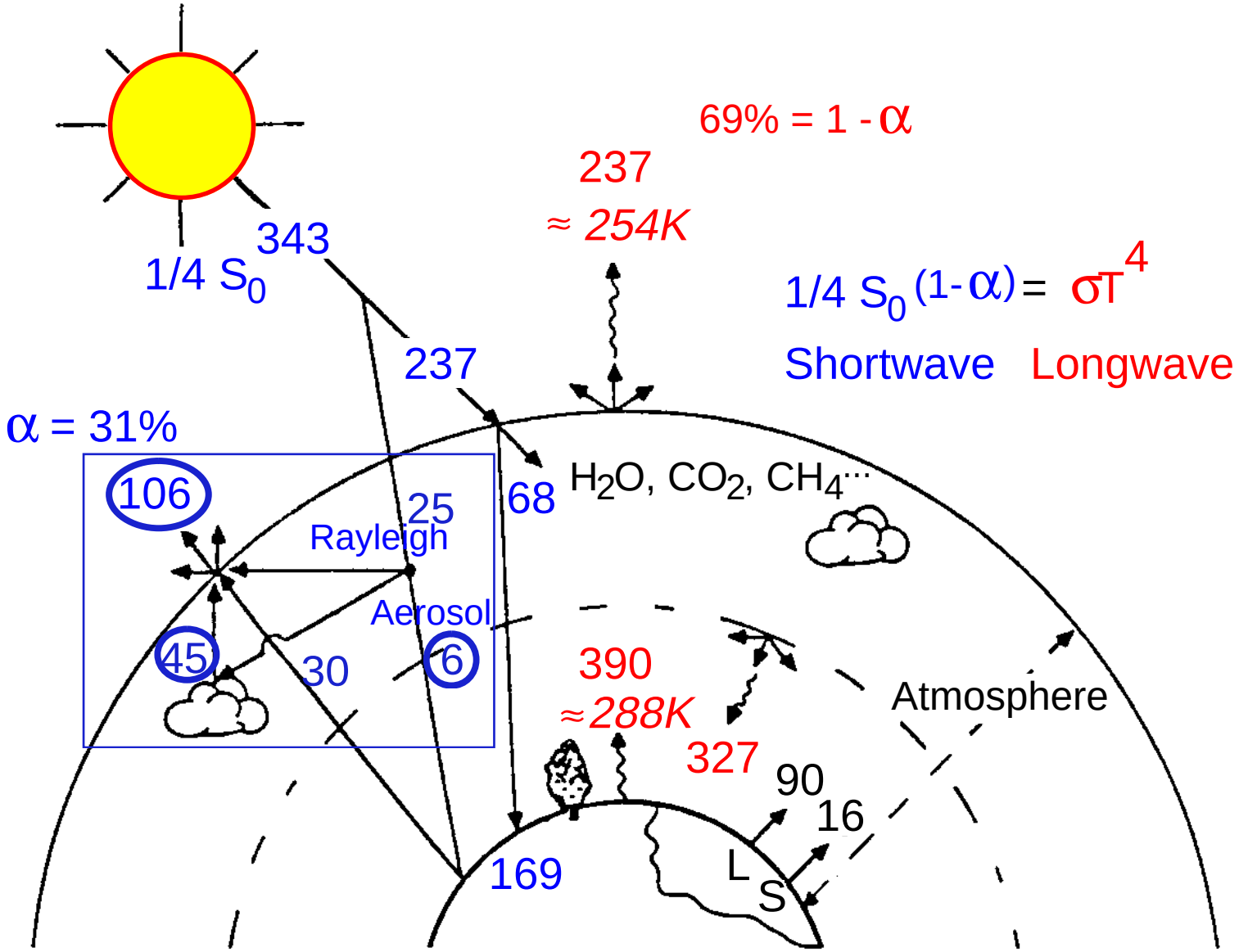
More droplets -- Enhanced cloud lifetime (Albrecht)

Semi-Direct Effect

Absorbing aerosol heats air and evaporates clouds

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Modified from Ramanathan, 1987

ELEMENTS OF AEROSOL FORCING

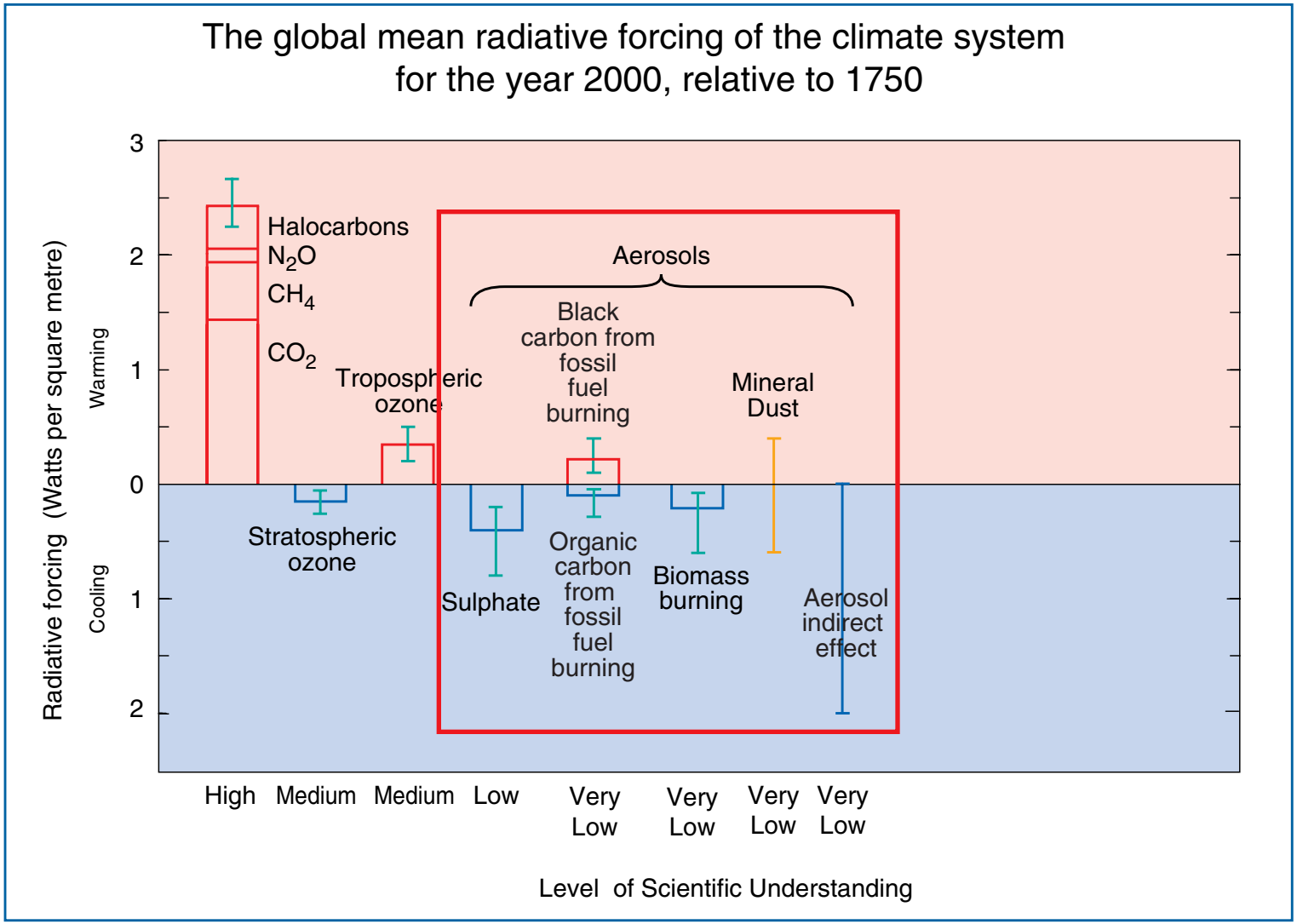
Forcing depends on ***amount of material*** present and on aerosol ***microphysical and optical properties*** (size, single scattering albedo, ability to nucleate cloud drops).

Amount of material present depends on ***emissions***, ***atmospheric chemistry***, and ***removal***.

Anthropogenic emissions are associated largely with ***fossil fuel combustion*** (sulfate, soot, secondary organics), ***biomass burning*** (organics and soot), ***mineral dust*** from disturbed soils.

Removal occurs mainly by precipitation with ***residence time of about a week***.

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
GHG's and aerosol direct and indirect effects



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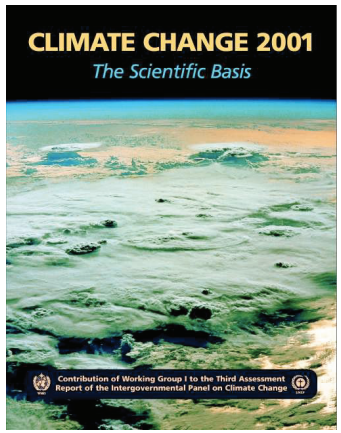


WHY SO LARGE UNCERTAINTY IN AEROSOL FORCING?

- ***Uncertainties in knowledge of atmospheric composition***

  Mass loading and chemical and microphysical properties and cloud nucleating properties of anthropogenic aerosols, and geographical distribution.

  At present and as a function of secular time.

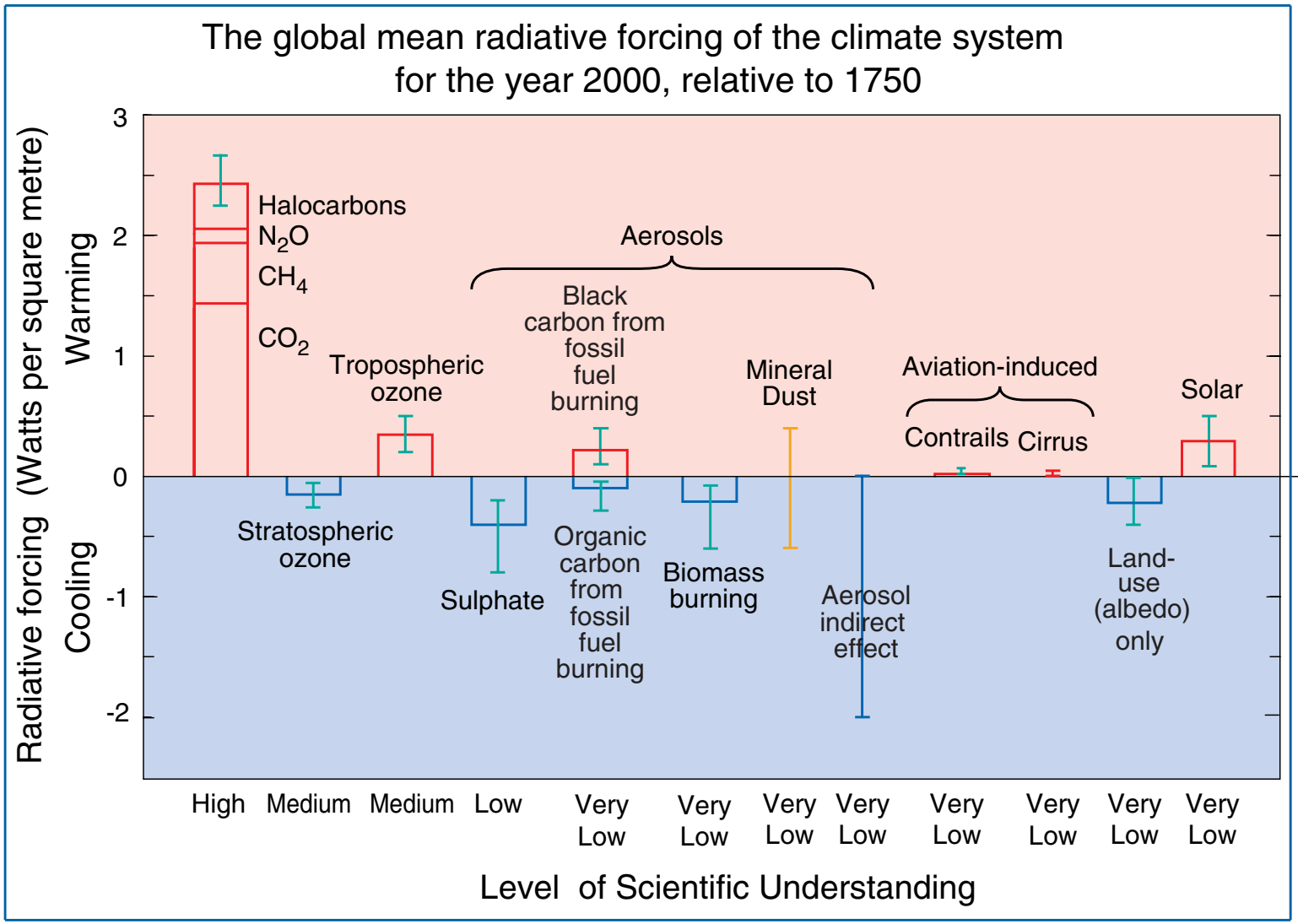
- ***Uncertainties in knowledge of atmospheric physics of aerosols***

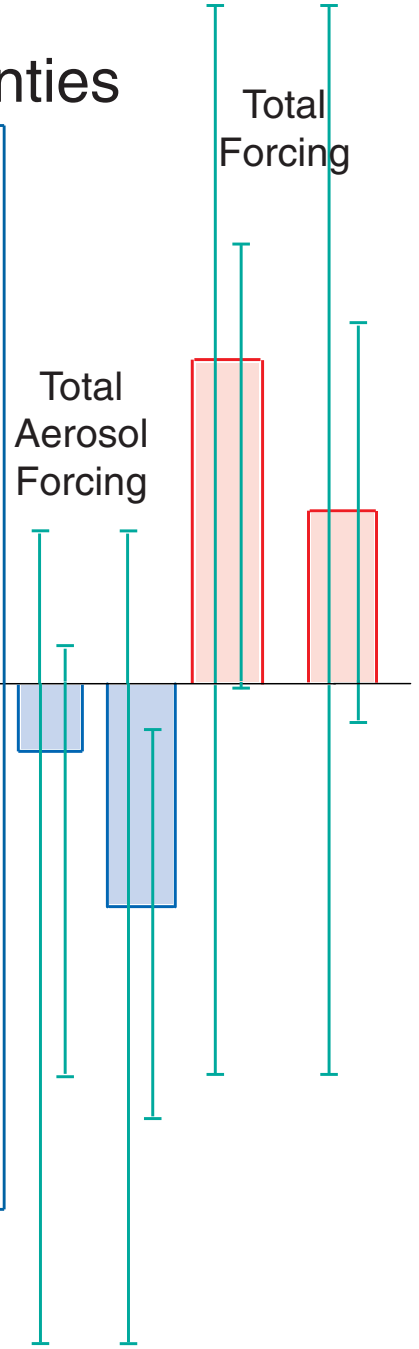
  Relating direct radiative forcing and cloud modification by aerosols to their loading and their chemical and microphysical properties.

The U.S. Department of Energy has initiated a new research program examining aerosol chemistry and physics pertinent to radiative forcing of climate change.

ADDING UP THE FORCINGS

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
With total aerosol forcing and total forcing and uncertainties





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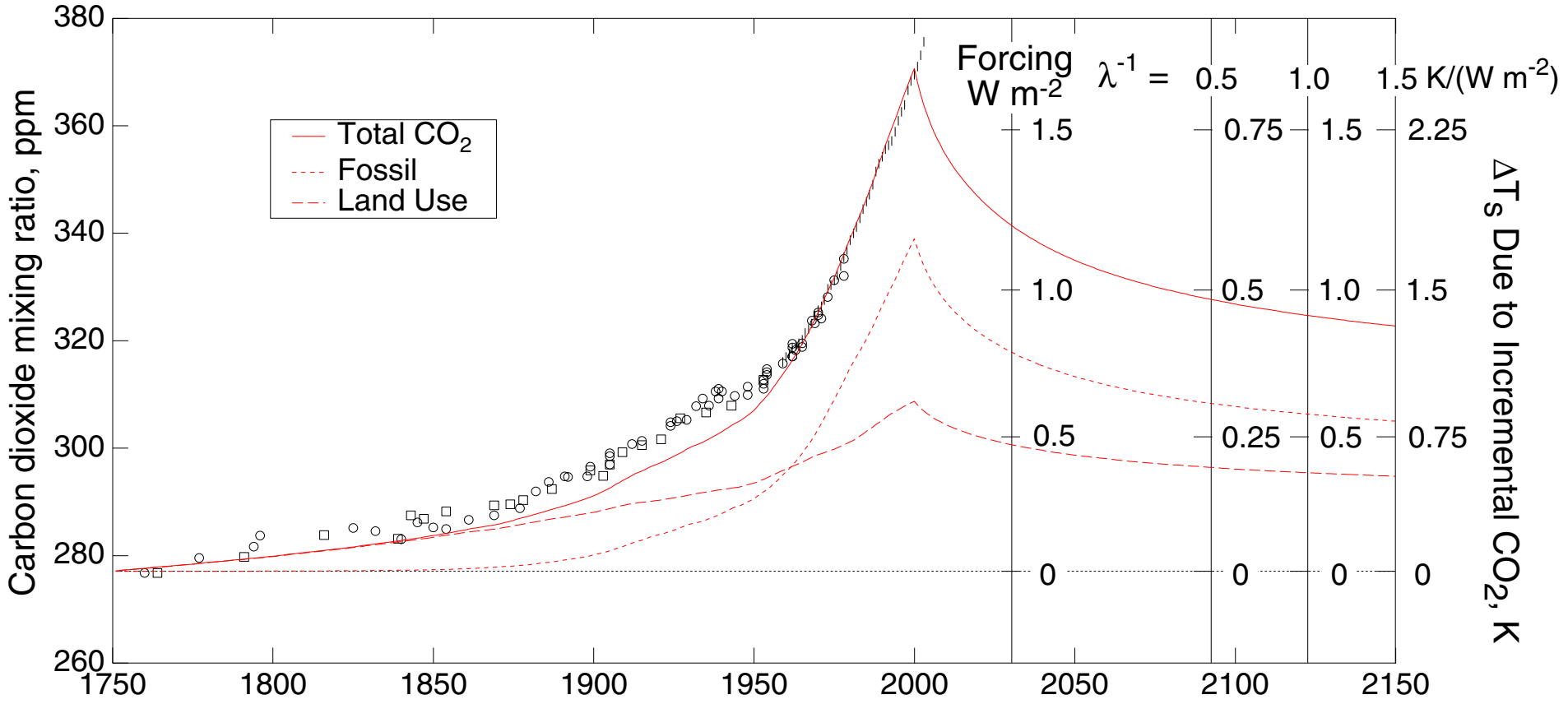
Schwartz, JAWMA, 2005

TEMPERATURE INCREASE

Projection of ***mixing ratio, forcing, and temperature increase*** due to anthropogenic emissions from 1750 to 2000



Climate sensitivity and actual increase depend on aerosol forcing.

This temperature increase will persist and will be additive to increases from future emissions.

IMPLICATIONS OF AEROSOL FORCING

- Aerosol negative (cooling) forcing is likely ***offsetting*** a substantial fraction of positive (warming) forcing by greenhouse gases.
- A substantial fraction of the forcing of 40 years of CO_2 emissions is being offset by ***a week's worth of aerosol***.
- The aerosol forcing is likely responsible for the ***low apparent climate sensitivity*** based on greenhouse gas forcing only.
- It is very likely that the global warming due to CO_2 and other GHG's is ***substantially greater*** than has been experienced thus far.
- The uncertainty in aerosol forcing and the resultant uncertainty in total forcing over the industrial period are so great as to ***preclude meaningful empirical inference of climate sensitivity and evaluation of climate models***.

SOME CONCLUDING OBSERVATIONS

- GHG concentrations and forcing are increasing. GHGs persist in the atmosphere for decades to centuries.
- Global mean temperature trends and many other indicia point to a warming world.
- Aerosol forcing is comparable to GHG forcing but much more uncertain. Aerosols are short-lived in the atmosphere.
- The sensitivity of the climate system is highly uncertain but is almost certainly substantially greater than is inferred based on GHG forcing alone.
- Decisions on GHG policy must be made in an uncertain world. Lack of controls on GHG emissions is also a decision.

Thank you

www.ecd.bnl.gov/steve