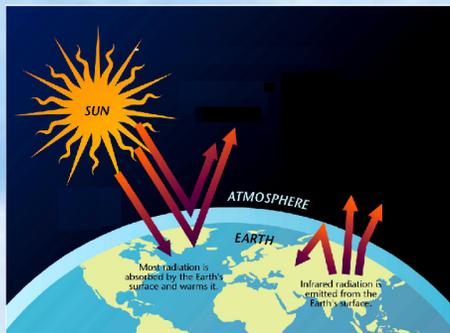
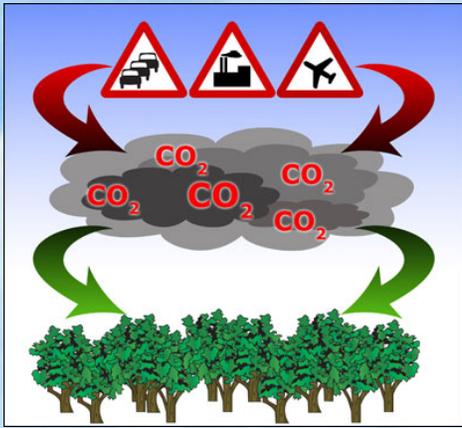




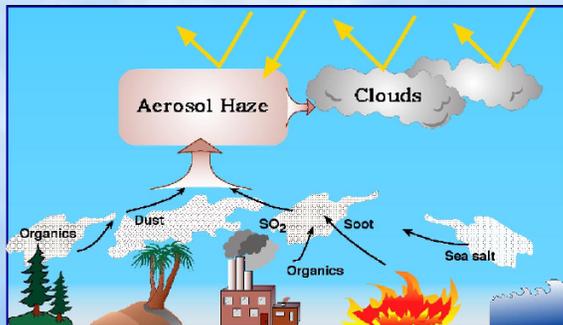
Fossil Energy, CO₂, Climate Change, and The Aerosol Problem

Stephen E. Schwartz

BROOKHAVEN
NATIONAL LABORATORY

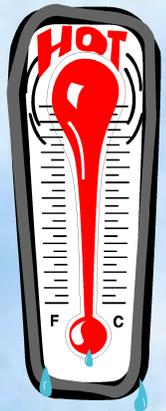


2011 IYC O₃ SYMPOSIUM ON STRATOSPHERIC OZONE AND CLIMATE CHANGE

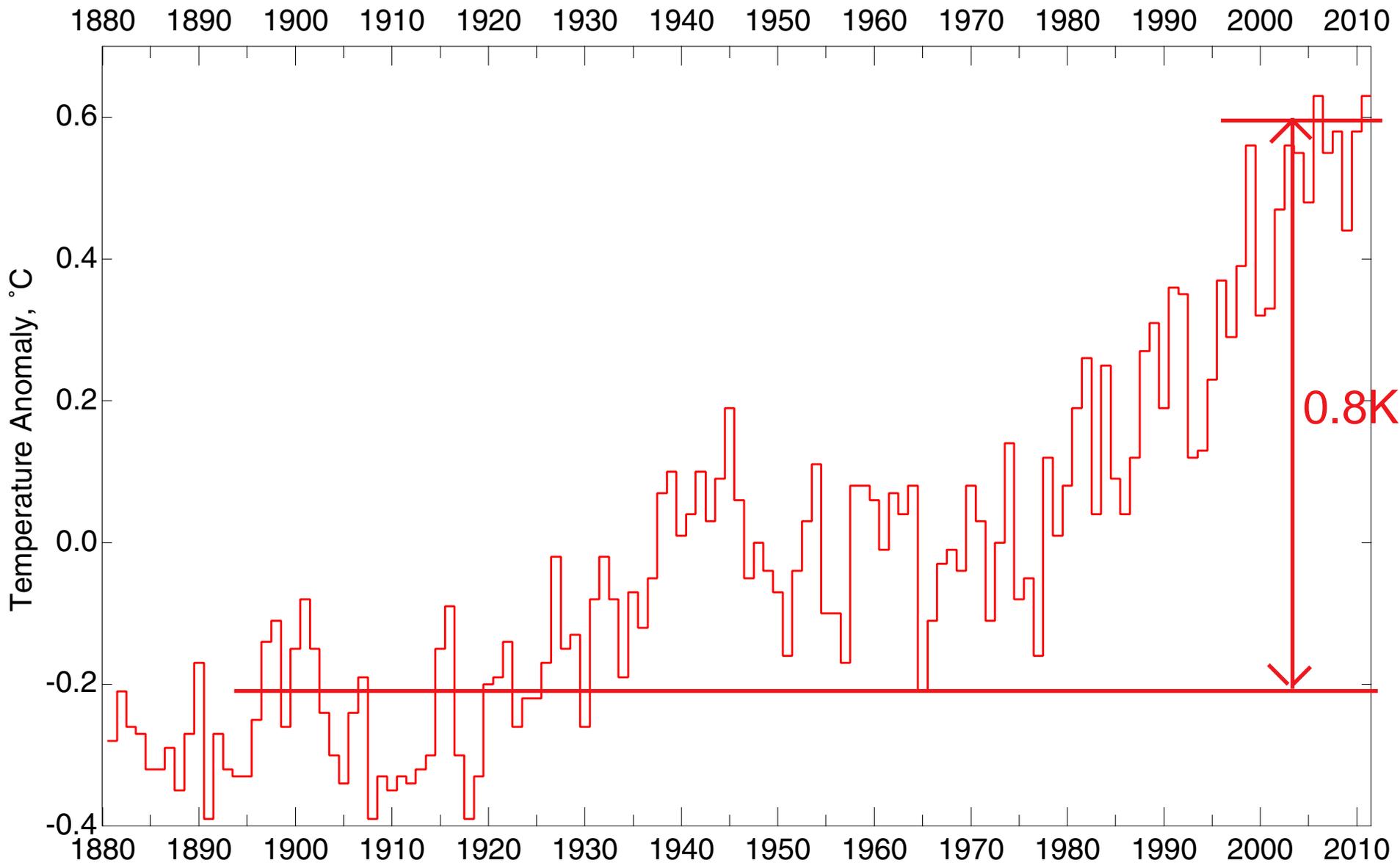


Washington, D.C. November 7-10, 2011

Viewgraphs available at www.ecd.bnl.gov/steve

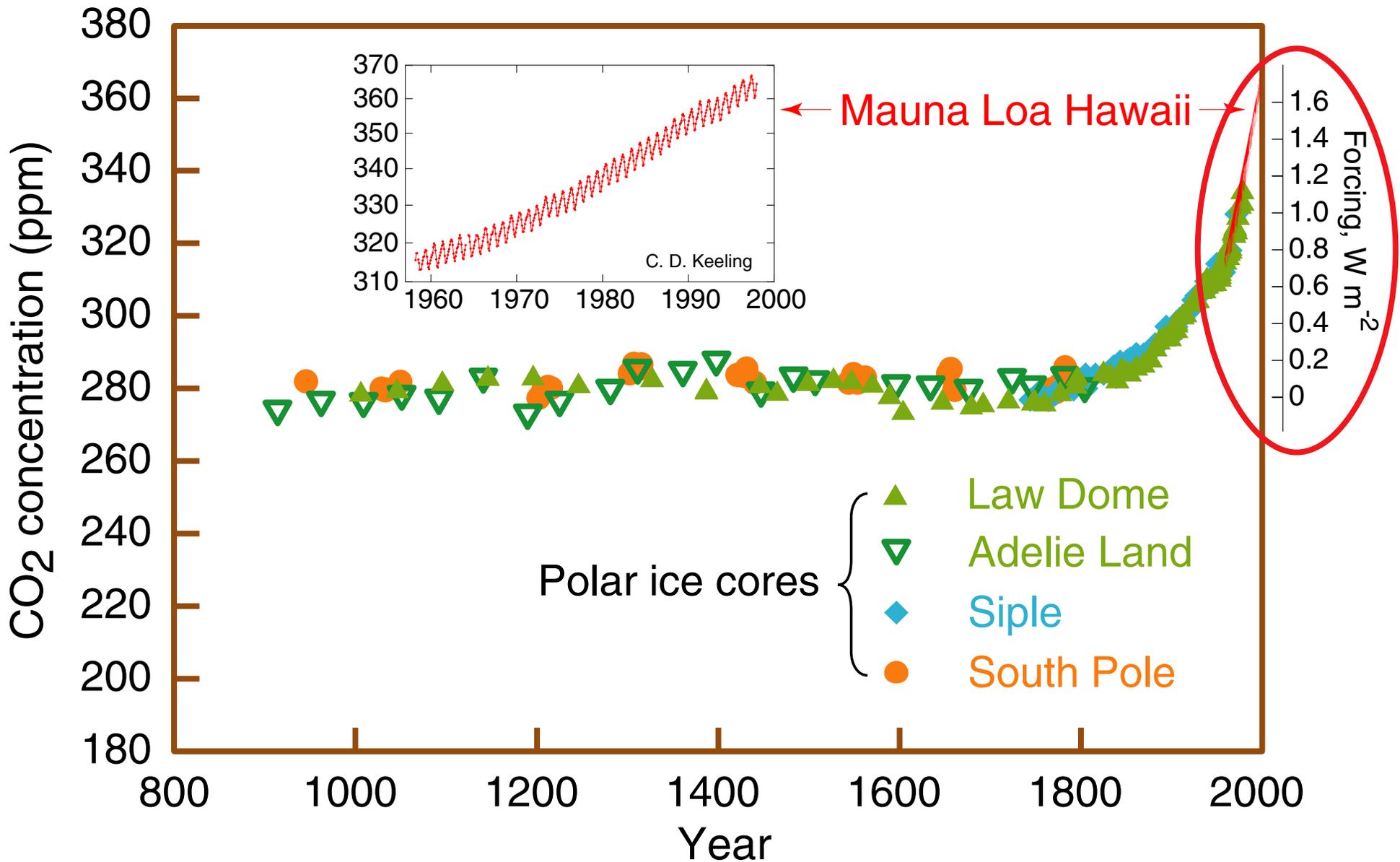


GLOBAL ANNUAL TEMPERATURE ANOMALY, 1880-2010



Data: Goddard Institute for Space Studies

ATMOSPHERIC CARBON DIOXIDE IS INCREASING



The increase in CO₂, a greenhouse gas, has produced a radiative forcing which is now 1.7 W m⁻².

RADIATIVE FORCING

An externally imposed *change* in Earth's radiation budget, F , $W\ m^{-2}$.

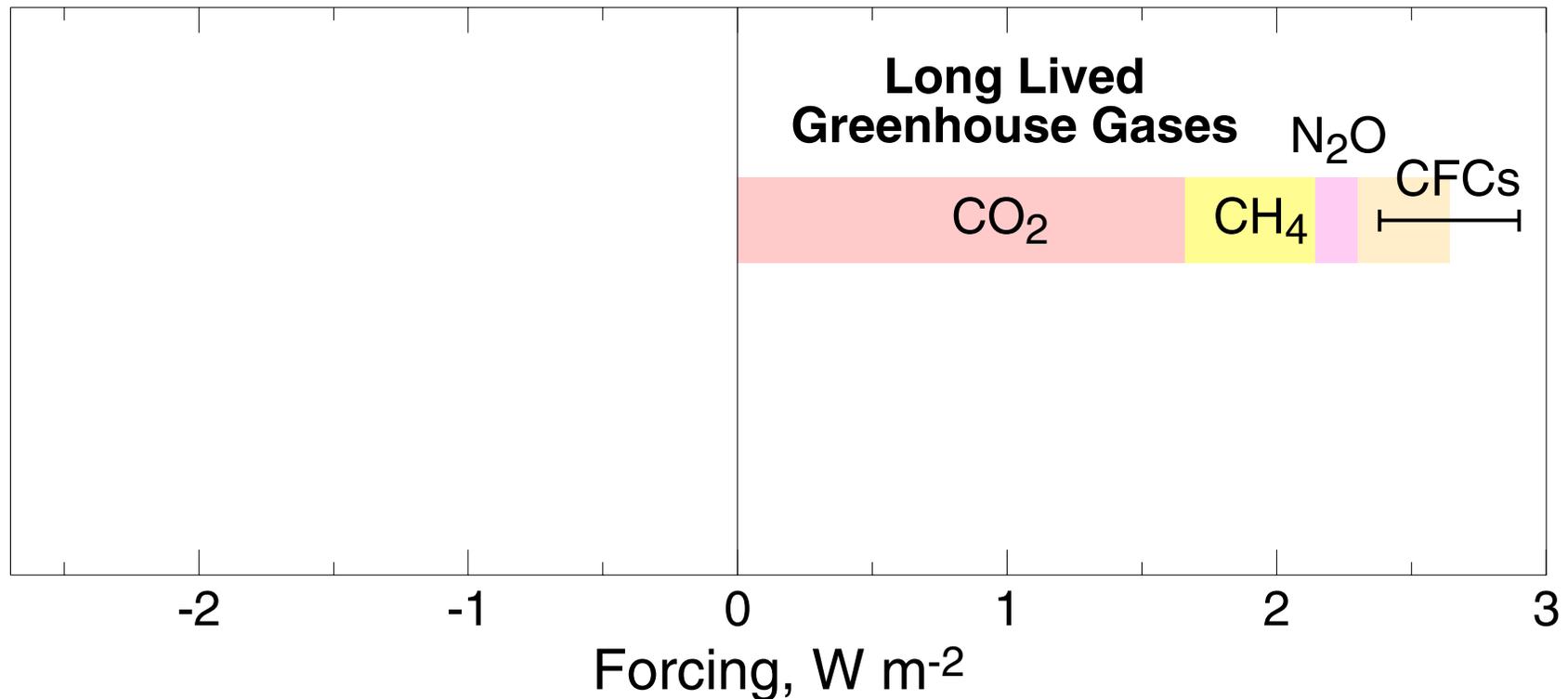
Working hypothesis:

On a global basis radiative forcings are additive and interchangeable.

- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.

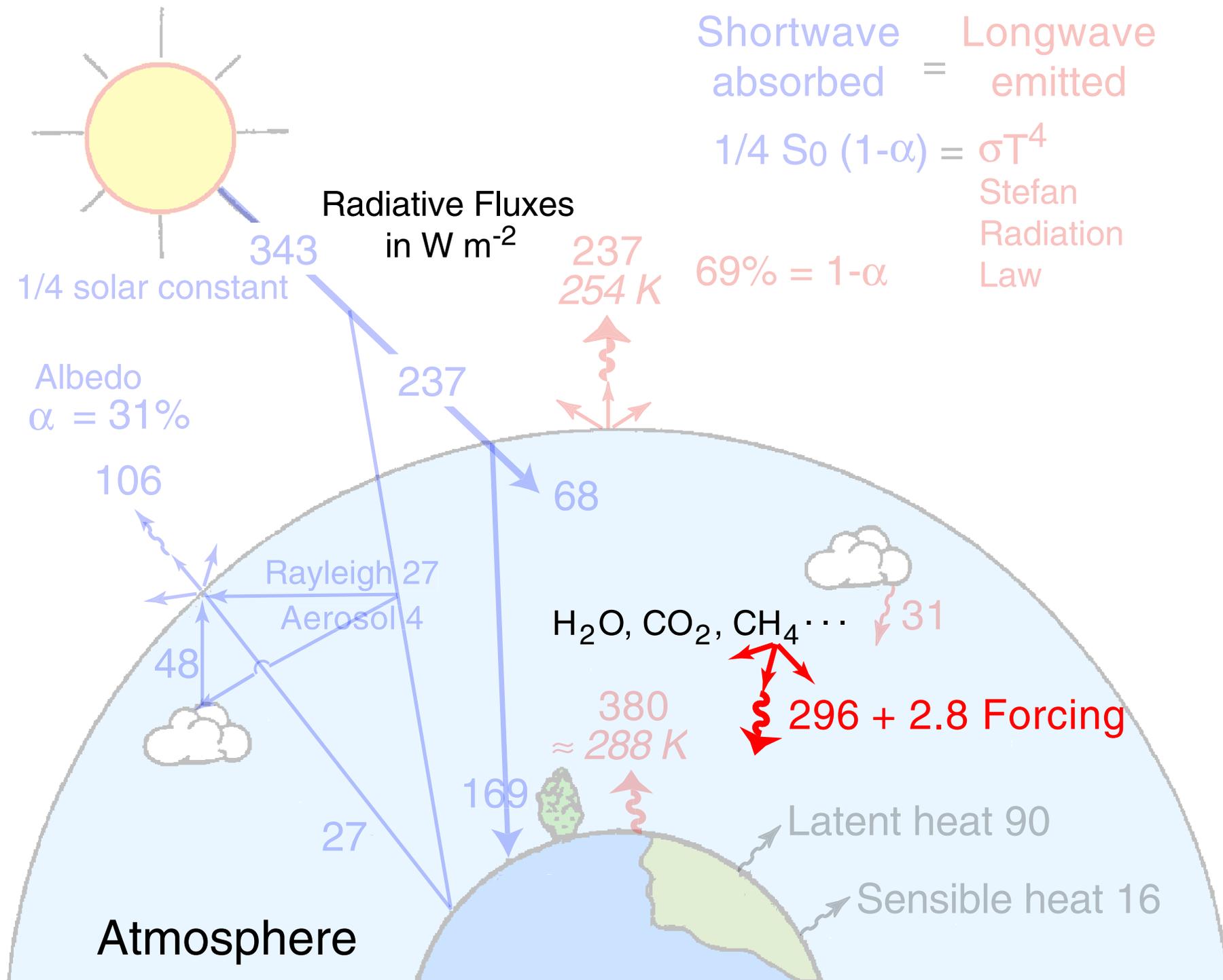
CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)



Gases are uniformly distributed; radiation transfer is well understood.
Greenhouse gas forcing is considered accurately known.

EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



CLIMATE SYSTEM RESPONSE

Increase in
global mean surface
temperature = Climate
sensitivity \times Effective
Forcing

$$\Delta T = S \times F_{\text{eff}}$$

S is Earth's *climate sensitivity*, units K / (W m⁻²)

F_{eff} is *effective forcing*, $F_{\text{eff}} = F - dH / dt$.

dH / dt is *planetary heating rate* determined mainly from ocean heat content measurements, 0.8 W m⁻².

For increases in CO₂, CH₄, N₂O, and CFCs over the industrial period, *forcing* $F = 2.8$ W m⁻².

Effective forcing $F_{\text{eff}} = 2.0$ W m⁻².

CO₂ DOUBLING TEMPERATURE

Climate sensitivity is commonly expressed as

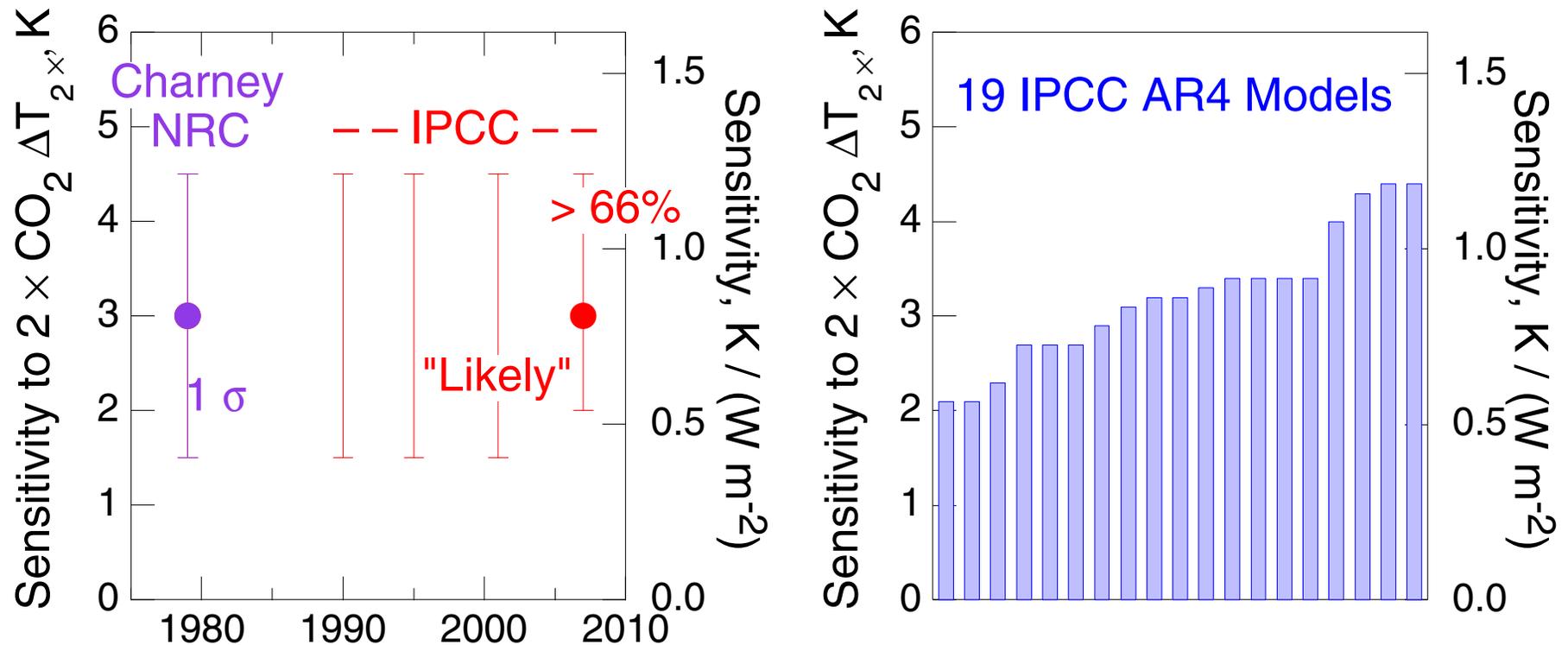
“CO₂ doubling temperature” unit K or °C

$$\Delta T_{2\times} \equiv S \times F_{2\times}$$

where $F_{2\times}$ is the CO₂ doubling forcing, *ca.* 3.7 W m⁻².

ESTIMATES OF EARTH'S CLIMATE SENSITIVITY AND ASSOCIATED UNCERTAINTY

Major national and international assessments and current climate models



Current estimates of Earth's climate sensitivity are centered about a CO₂ doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty.

Range of sensitivities of current models roughly coincides with IPCC “likely” range.

EXPECTED WARMING

For increases in CO₂, CH₄, N₂O, and CFCs over the industrial period, *forcing* $F = 2.8 \text{ W m}^{-2}$,

Planetary heating rate $dH / dt = 0.8 \text{ W m}^{-2}$,

Effective forcing $F_{\text{eff}} = F - dH / dt = 2.0 \text{ W m}^{-2}$,

CO₂ doubling forcing $F_{2\times} = 3.7 \text{ W m}^{-2}$,

IPCC best estimate *doubling temperature* $\Delta T_{2\times} = 3 \text{ }^\circ\text{C}$,

The *expected temperature increase* is

$$\Delta T_{\text{exp}} = \frac{F_{\text{eff}}}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.0}{3.7} \times 3 \text{ }^\circ\text{C} = 1.6 \text{ }^\circ\text{C}$$

THE WARMING DISCREPANCY

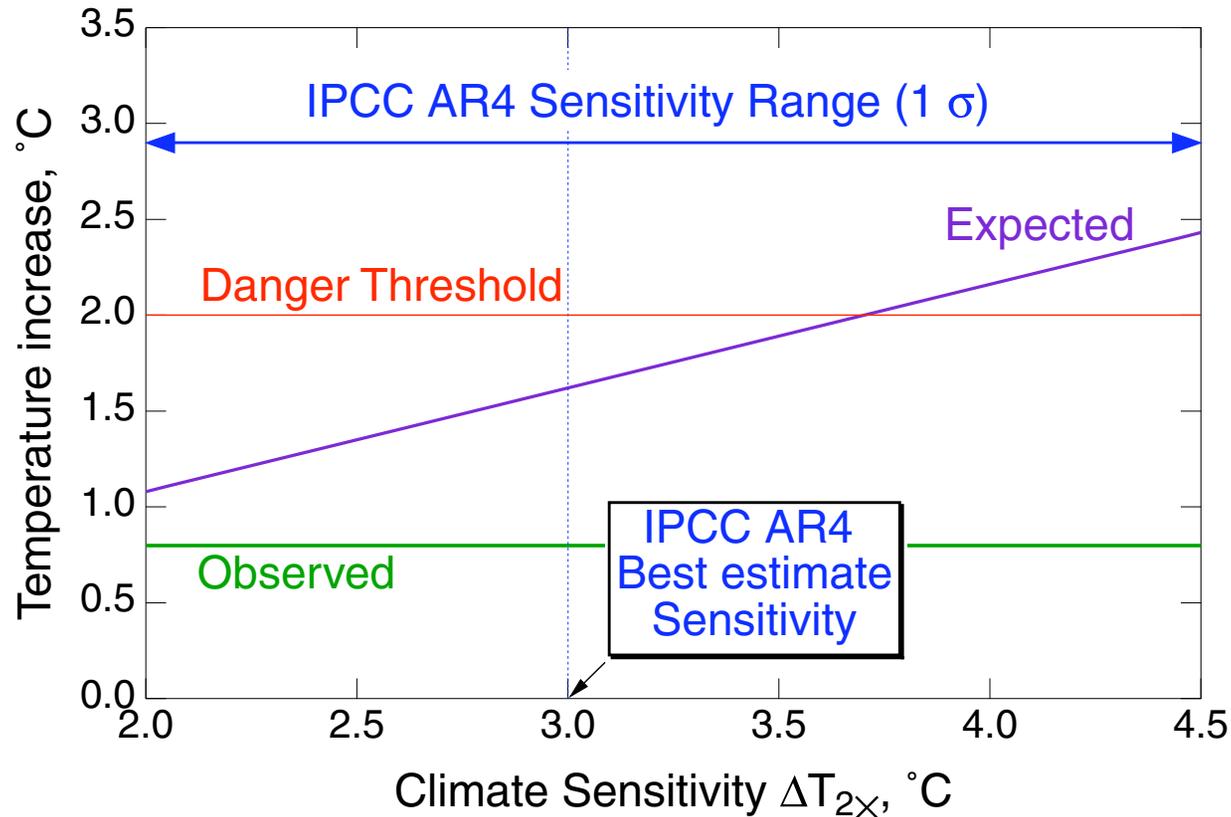
Expected temperature increase: $\Delta T_{\text{exp}} = 1.6 \text{ }^\circ\text{C}$

Observed temperature increase: $\Delta T_{\text{obs}} = 0.8 \text{ }^\circ\text{C}$

How can we account for this *warming discrepancy*?

EXPECTED TEMPERATURE INCREASE

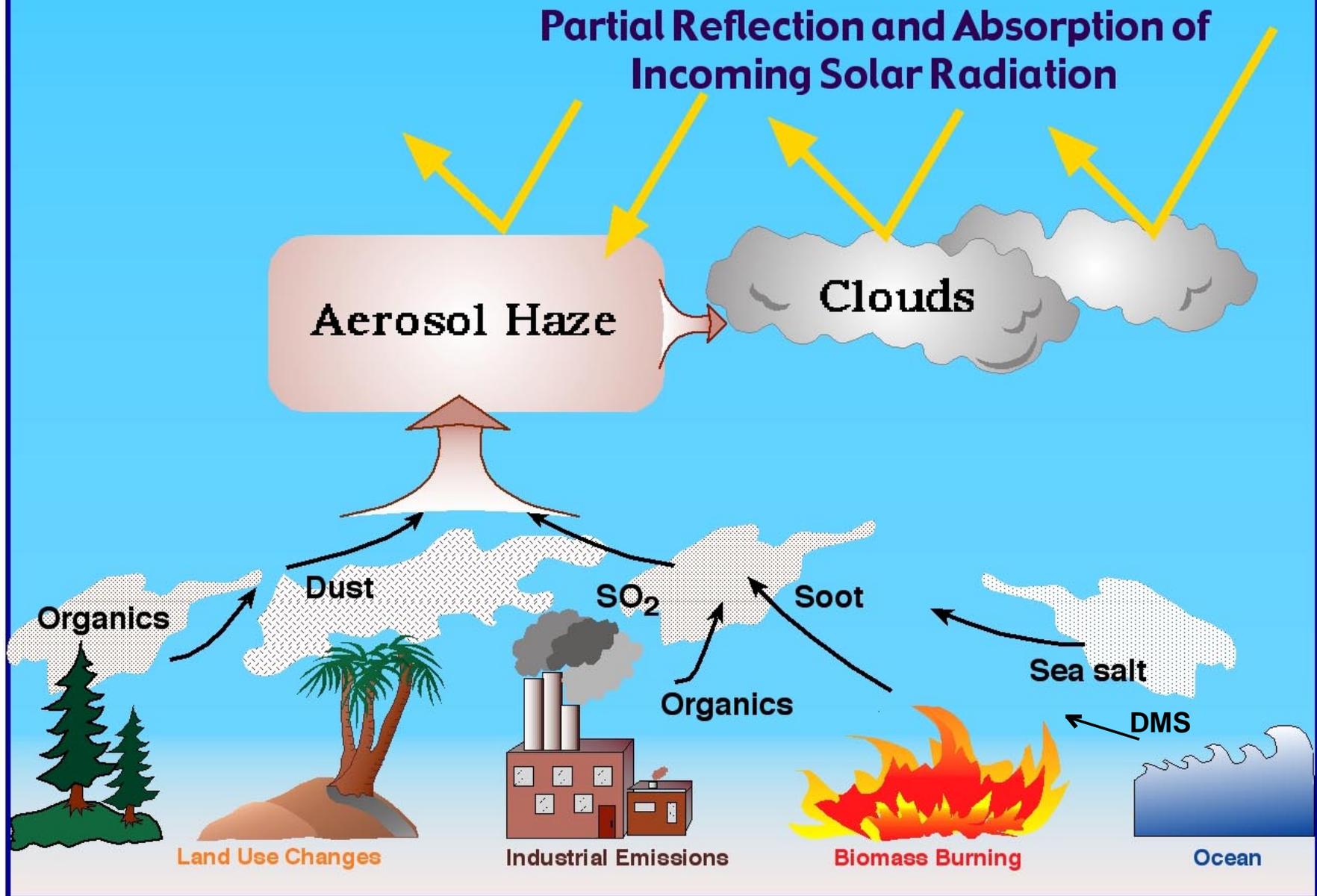
Based on greenhouse gas forcing only, 2.8 W m^{-2} , with planetary heating rate 0.8 W m^{-2} (effective forcing 2.0 W m^{-2})



Expected temperature increase exceeds observed for entire IPCC (2007) sensitivity range.

Depending on sensitivity, expected temperature increase approaches or exceeds 2°C , widely accepted threshold for onset of dangerous anthropogenic interference with the climate system.

Radiative Forcing by Tropospheric Aerosol



AEROSOL IN MEXICO CITY BASIN



Photo credit: Berk Knighton

AEROSOL IN MEXICO CITY BASIN

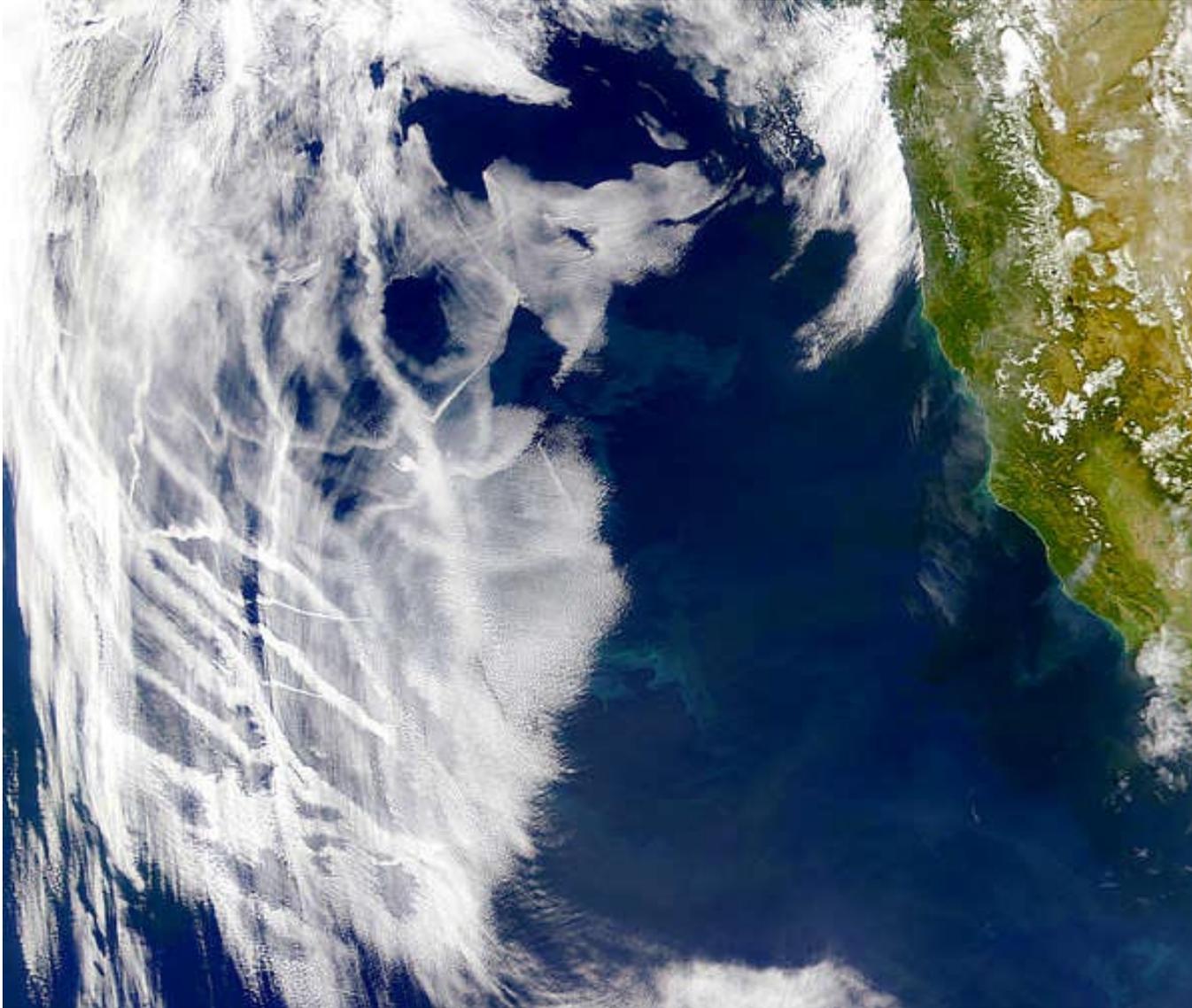


Photo credit: Berk Knighton

Light scattering by aerosols decreases absorption of solar radiation.

CLOUD BRIGHTENING BY SHIP TRACKS

Satellite photo off California coast

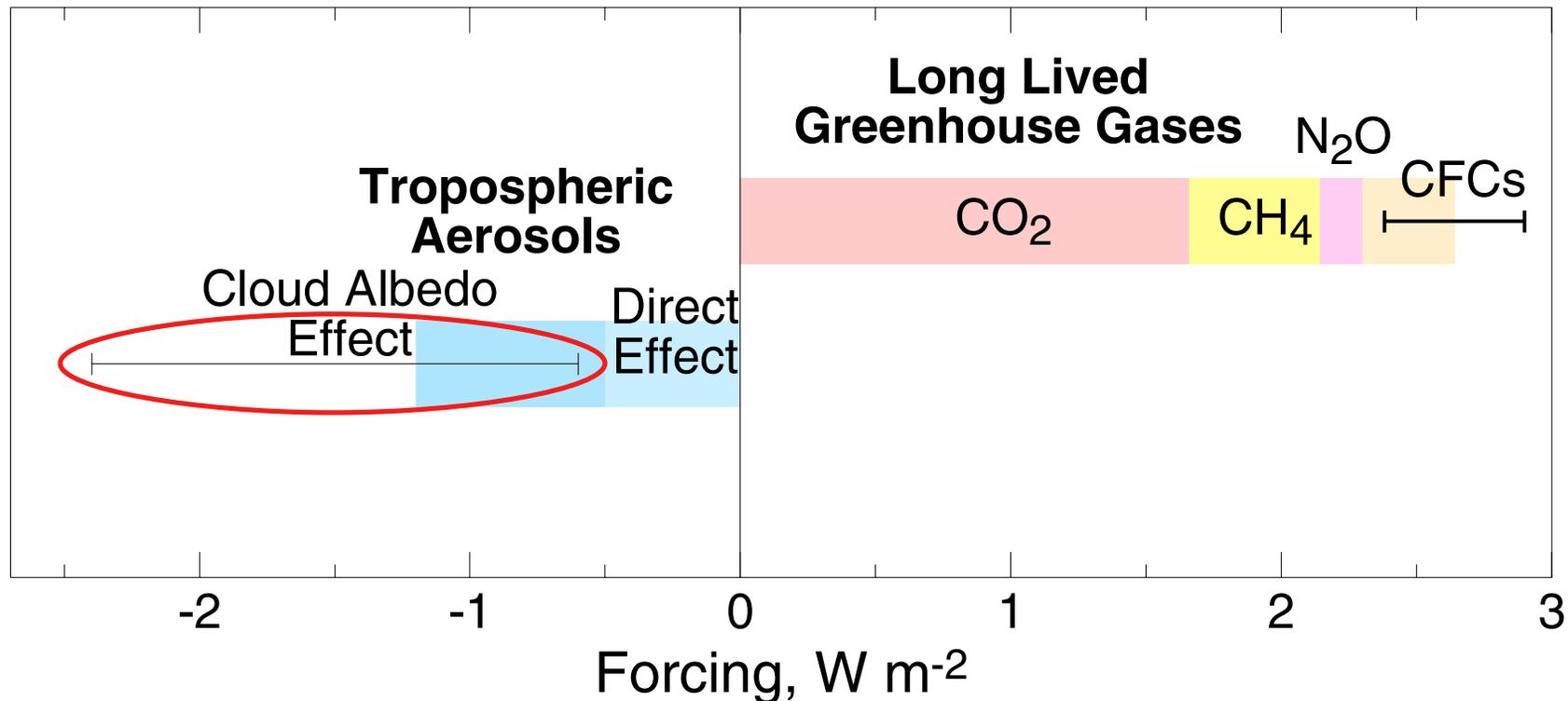


Credit: SeaWiFS

Aerosols from ship emissions enhance reflectivity of marine stratus.

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)



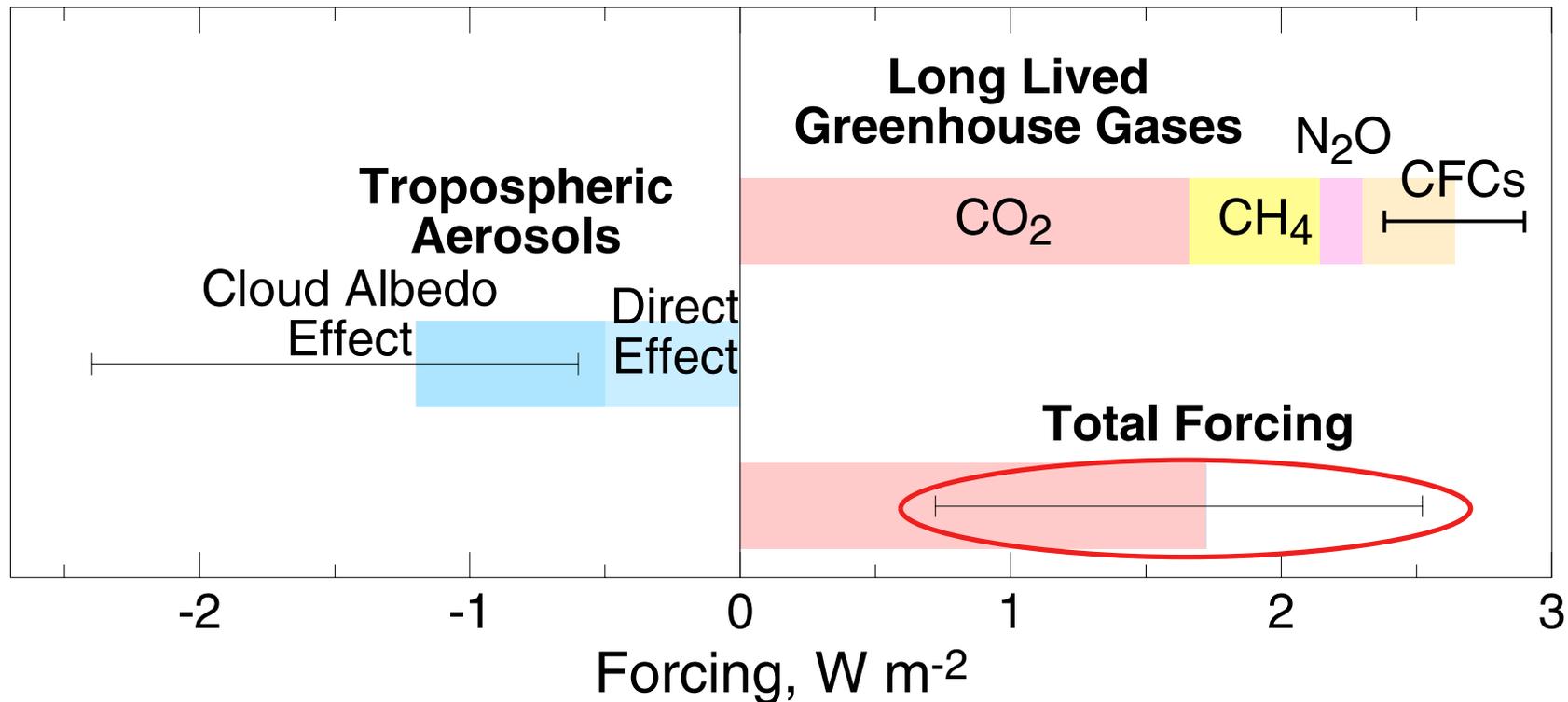
Aerosols exert a negative (cooling) forcing, opposite to greenhouse gases.

Aerosols are heterogeneous in space, time, composition, and size.

Uncertainty in aerosol forcing is much larger than uncertainty in greenhouse gas forcing.

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)

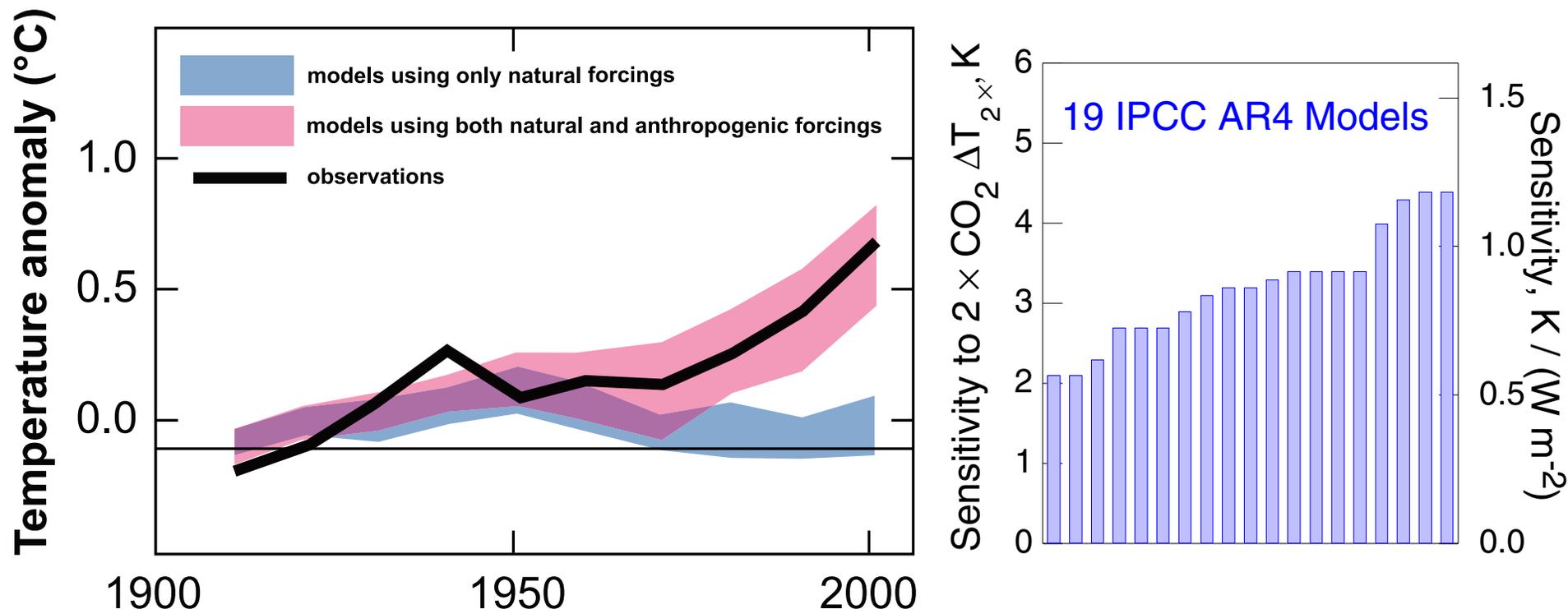


Aerosol forcing may offset much of the greenhouse gas forcing.

Uncertainty in total forcing is dominated by uncertainty in aerosol forcing.

OBSERVED AND MODELED WARMING

Ensemble of 58 model runs with 14 global climate models



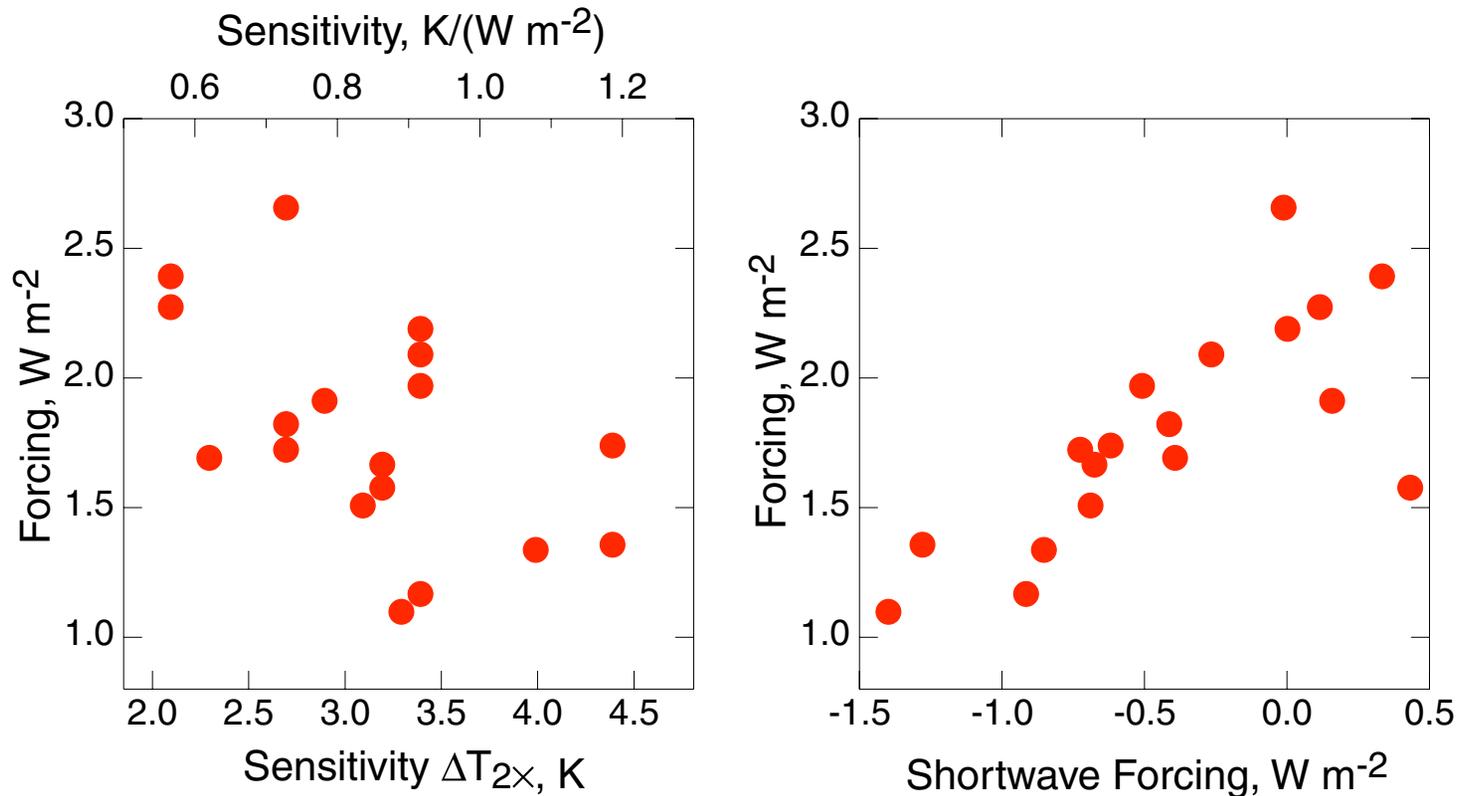
- “ Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a *consistent explanation of the observed temperature record*.
- “ These simulations used models with *different climate sensitivities, rates of ocean heat uptake and magnitudes and types of forcings*.

How can this be?

IPCC AR4, 2007

CORRELATION OF FORCING AND SENSITIVITY IN CLIMATE MODELS

18 IPCC 2007 climate models



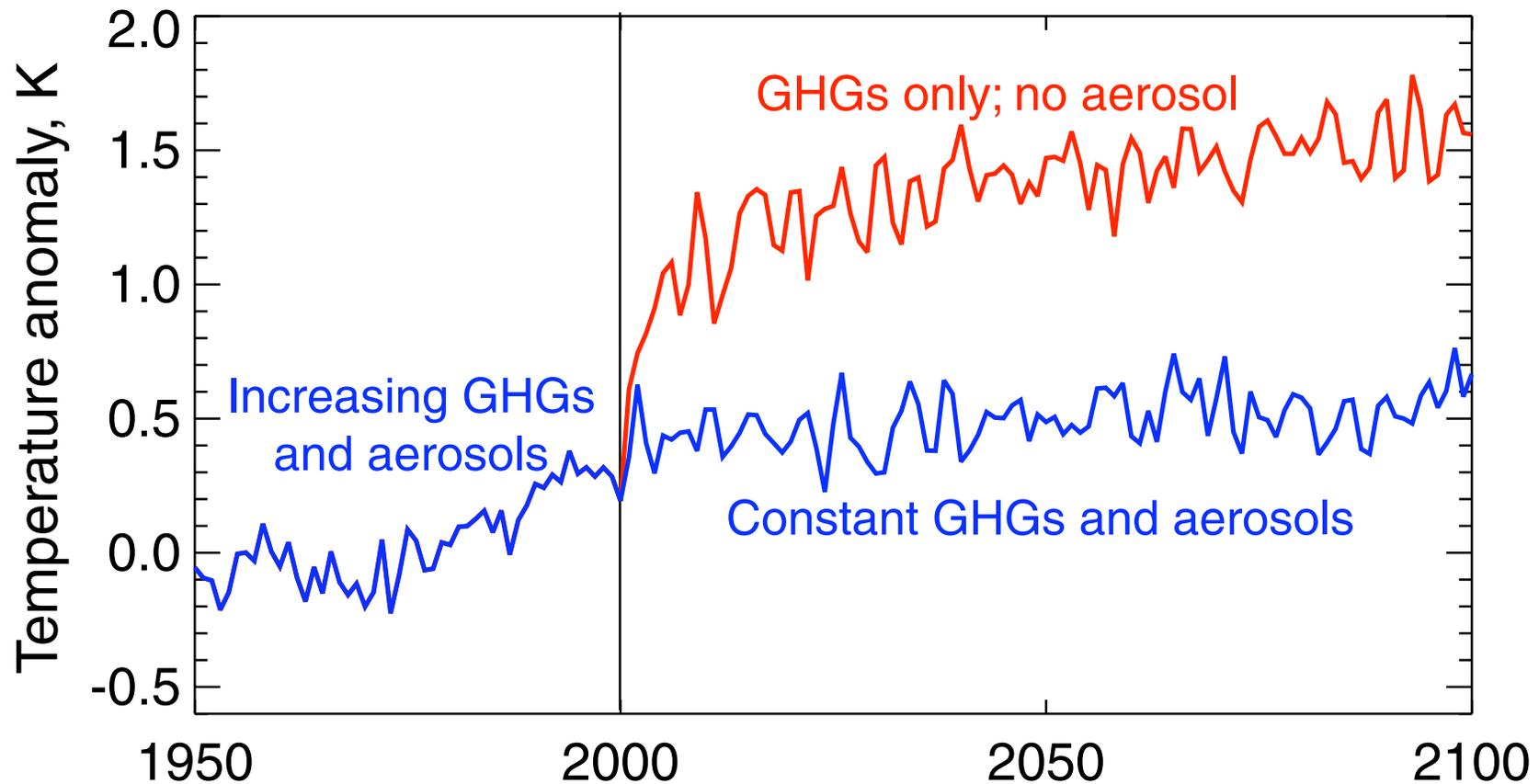
After Kiehl (2007); data from Forster and Taylor (2006)

To reproduce observed 20th century temperature increase, models with low sensitivity employ large forcing, and vice versa.

Variation in forcing is due mainly to variation in aerosol (shortwave) forcing.

GLOBAL TEMPERATURE RESPONSE TO TURNING OFF AEROSOL EMISSIONS

Experiment with ECHAM-5 GCM



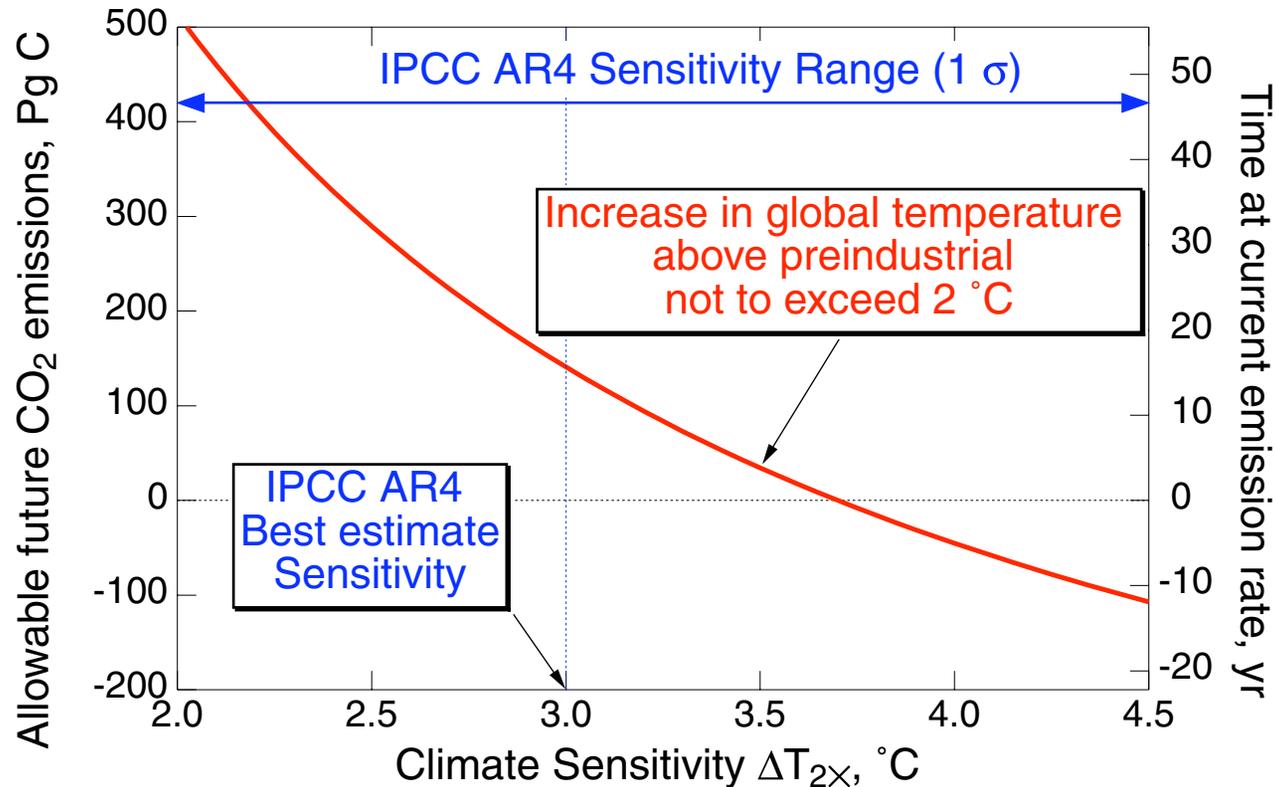
Modified from Brasseur and Roeckner, GRL, 2005

For constant GHGs and aerosols, temperature remains near year 2000 value. Without aerosol offset to GHG forcing temperature rapidly increases. However the magnitude of the aerosol offset is unknown.

ALLOWABLE FUTURE CO₂ EMISSIONS

Such that committed increase in global mean temperature not exceed 2°C

Greenhouse gas forcing only, with planetary heating rate 0.8 W m⁻²



For IPCC best-estimate sensitivity, only about 15 years more emissions at current rates.

At current emission rates, for IPCC sensitivity range, allowable emissions range from +60 years to -10 years.

CONCLUSIONS AND IMPLICATIONS

- Future climate response to greenhouse gases depends strongly on climate sensitivity.
- Climate sensitivity is *highly uncertain*.
- Constraining climate sensitivity is essential to planning the nation's and the world's energy future.
- *The expected increase in global temperature* from existing incremental concentrations of long-lived greenhouse gases *substantially exceeds the observed increase*.
- This is due to some mix of *aerosol forcing* offsetting GHG forcing and/or *climate sensitivity lower than the IPCC best estimate*.
- Constraining climate sensitivity requires *major reduction in uncertainty in aerosol forcing*.

... cont'd

CONCLUSIONS AND IMPLICATIONS

... *cont'd*

- Because aerosols are short-lived in the atmosphere, the offset of greenhouse-gas warming by aerosols only postpones the inevitable warming.
- As aerosols and precursor gases are largely co-emitted with fossil CO₂, reduction or cessation of CO₂ emissions will likely result in *rapid, substantial increase in global temperature* due to decrease in offsetting forcing by aerosols.
- Allowable future CO₂ emissions correspond at most to *a few decades at present emission rates*.
- Because of the central role of fossil fuels in the world's energy economy and the intrinsic production of CO₂, *solving the CO₂ climate problem will be much tougher than solving the stratospheric ozone problem*, widely viewed as a precedent for the needed concerted global action.