

CLIMATE CHANGE: A REALLY TOUGH SCIENTIFIC PROBLEM

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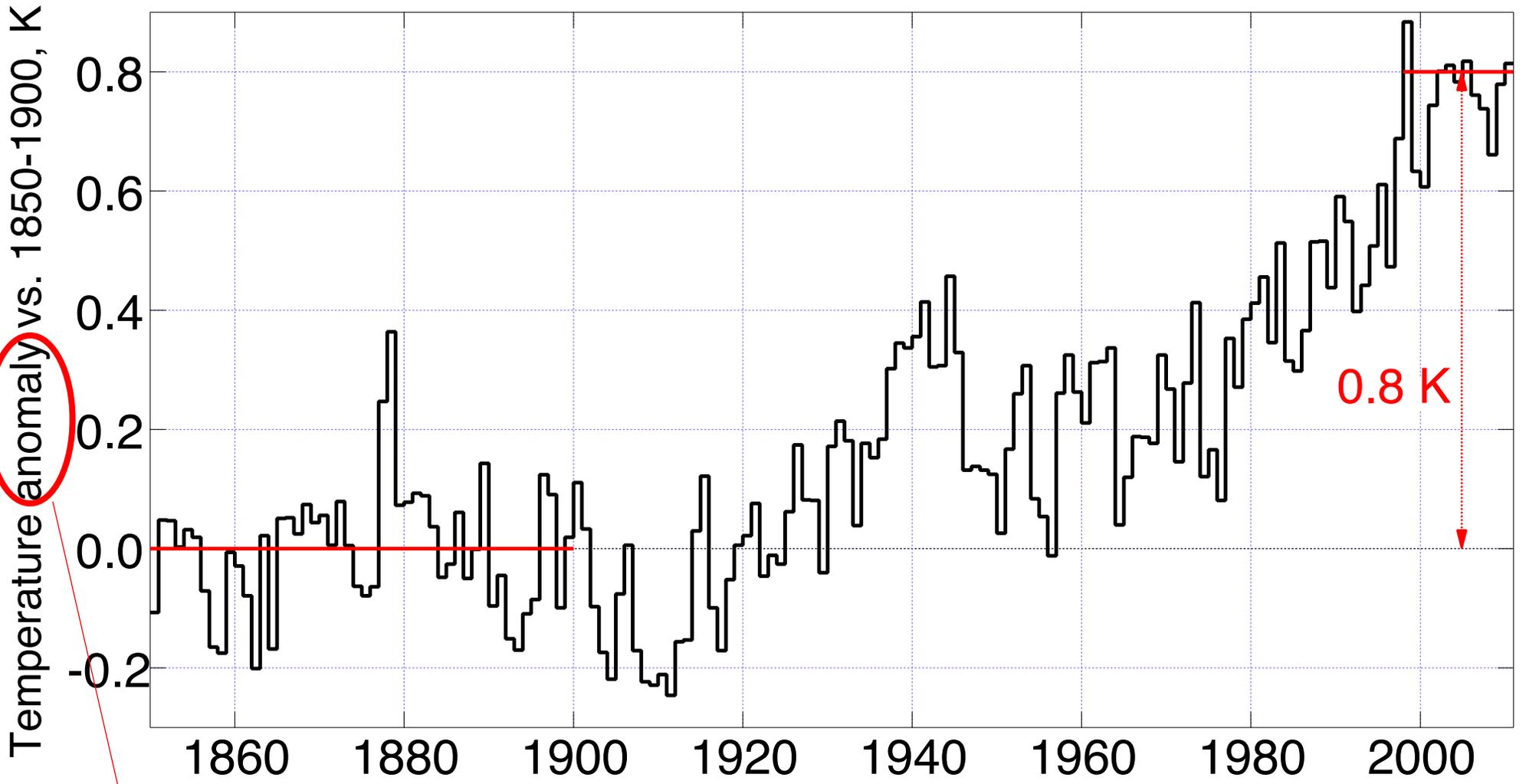
Physics 311: Connections in Science “Energy Problems”

Stony Brook University

September 26, 2013

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

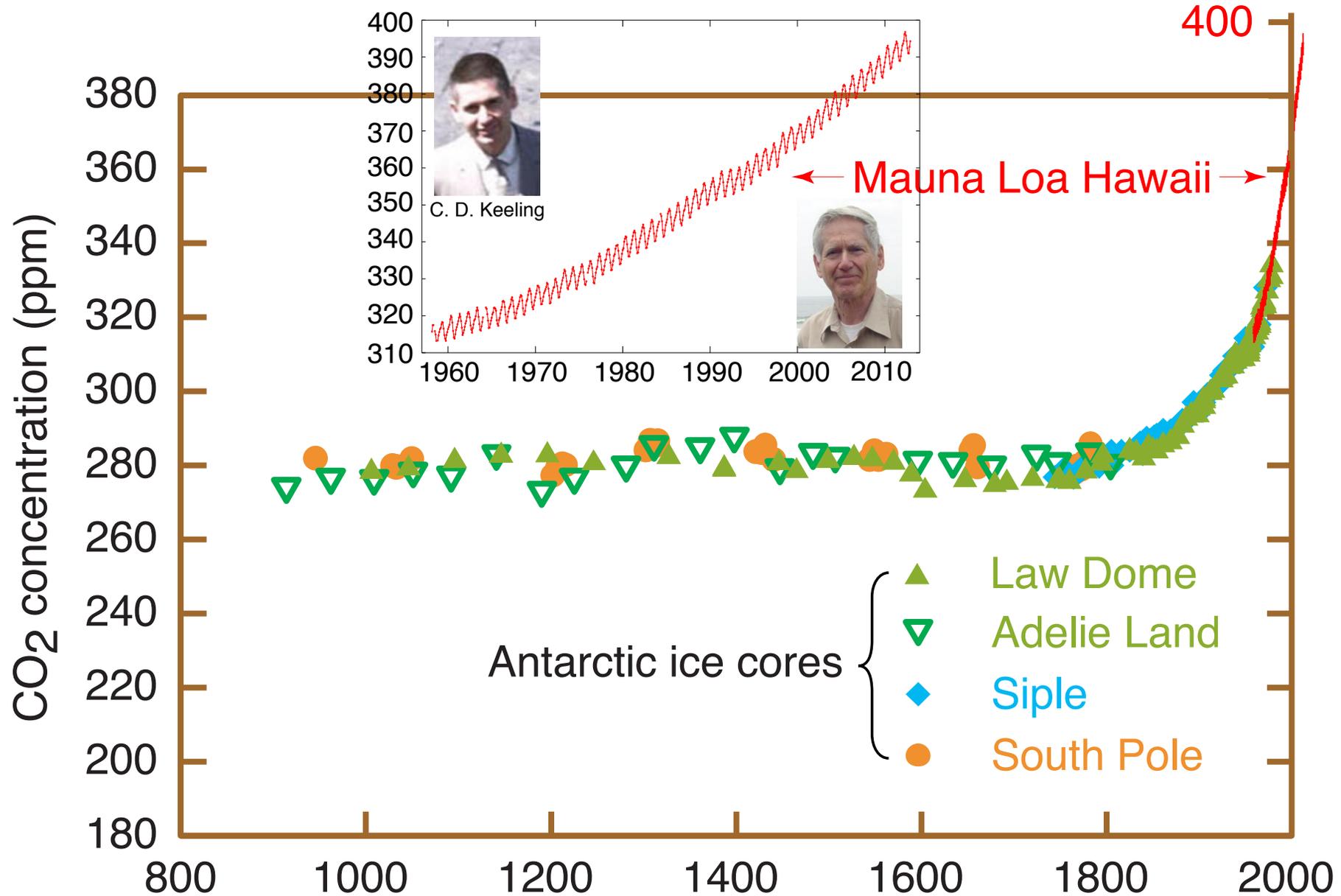
GLOBAL TEMPERATURE CHANGE SINCE 1850



Climatic Research Unit, East Anglia, UK

Departure from climatological average

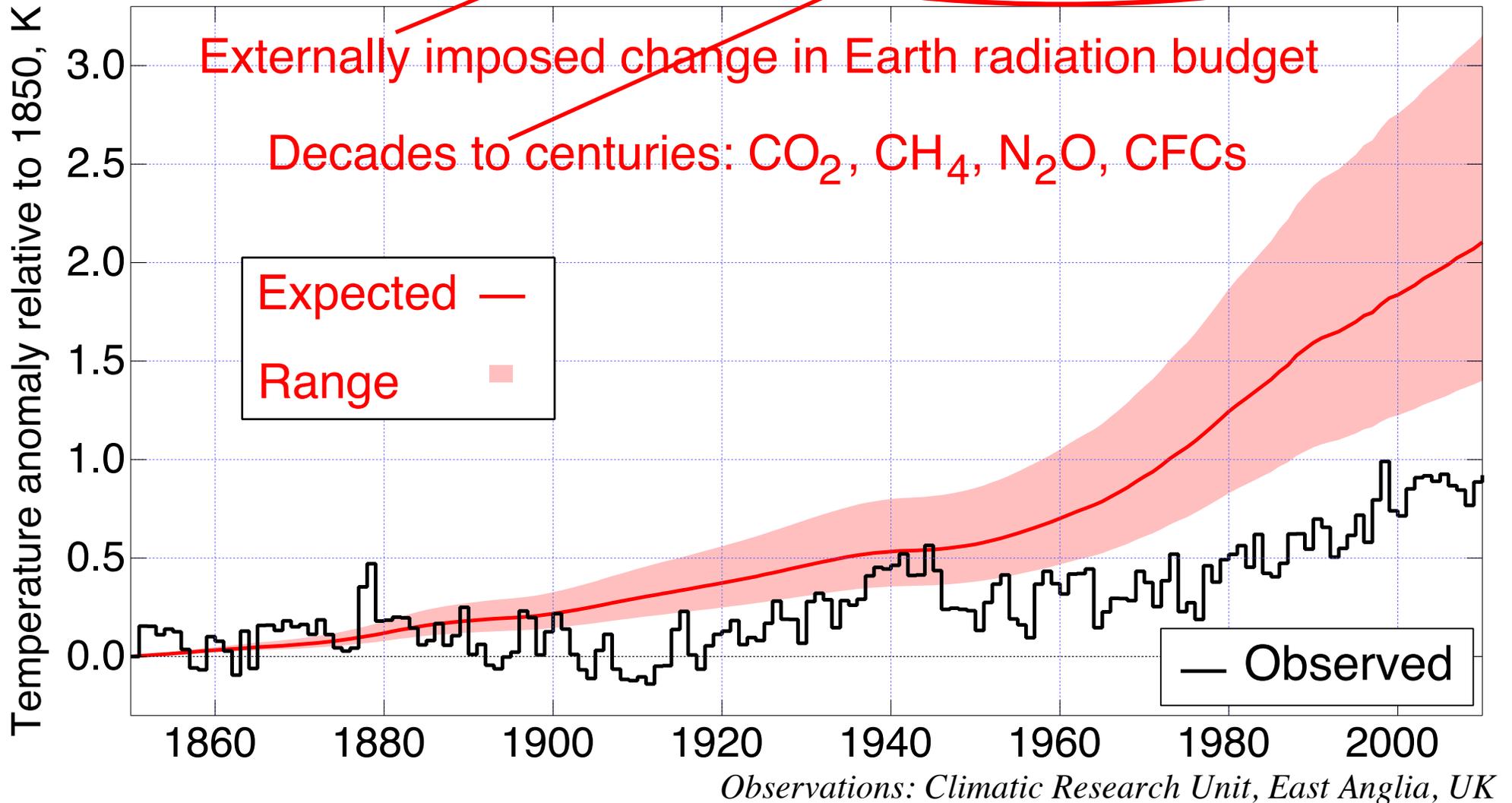
ATMOSPHERIC CARBON DIOXIDE IS INCREASING



Global carbon dioxide concentration over the last thousand years

EXPECTED AND OBSERVED TEMPERATURE CHANGE OVER THE TWENTIETH CENTURY

Expected warming for forcing by long-lived greenhouse gases only



Expected increase substantially exceeds observed.

2009 **COPENHAGEN ACCORD** AGREES ON 2°C MAXIMUM TEMPERATURE RISE

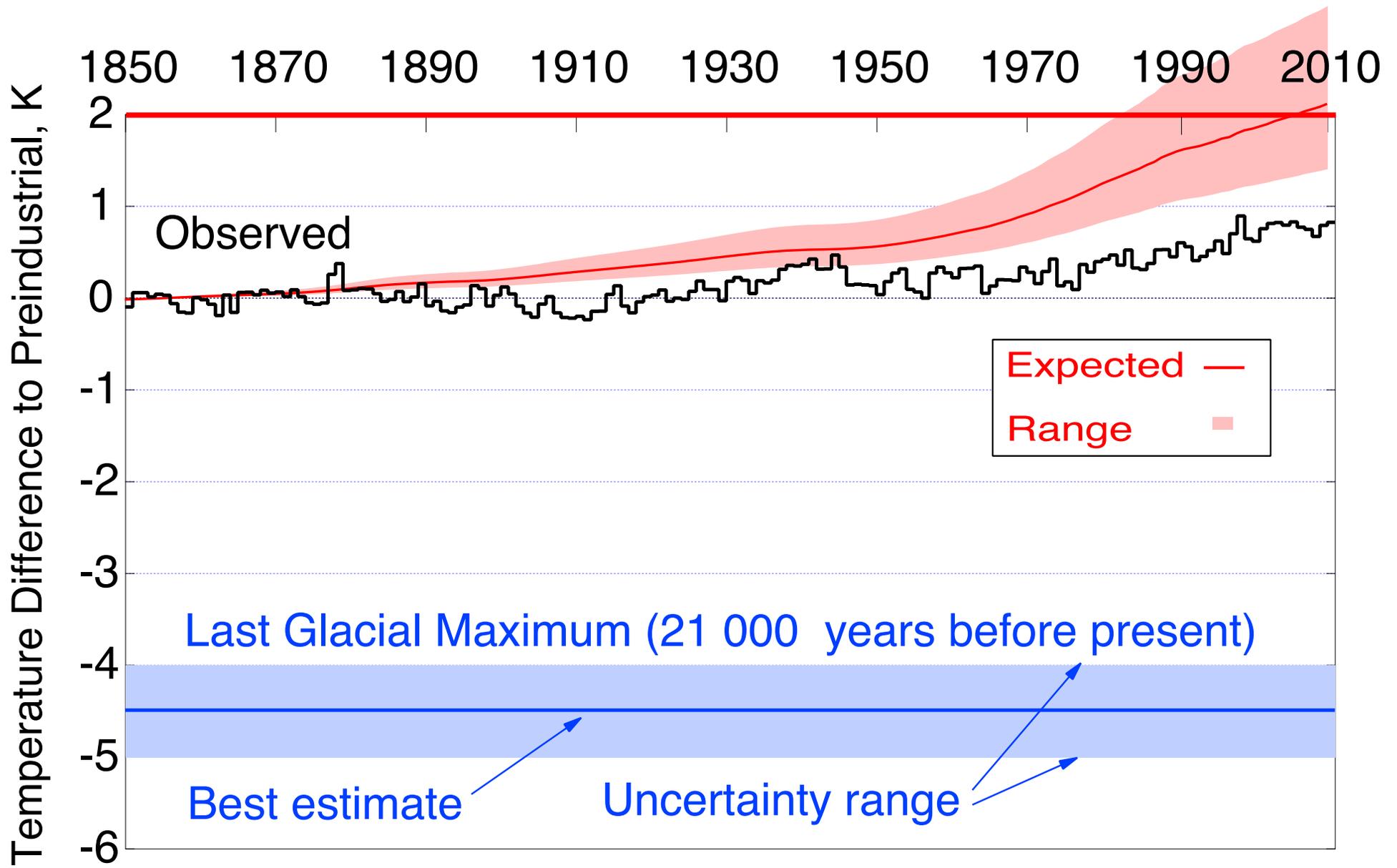
The Heads of State, Heads of Government, Ministers . . . present at the United Nations Climate Change Conference 2009 in Copenhagen:

Albania, Algeria, Armenia, Australia, Austria, . . . [106 countries]
. . . , *United States of America*, Uruguay and Zambia, *have agreed*
on this Copenhagen Accord. . . .

We underline that climate change is one of the greatest challenges of our time. We emphasise our strong political will to urgently combat climate change. . . .

To . . . *stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*, we shall, *recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius* . . . enhance our long-term cooperative action to combat climate change.

4½ DEGREES OF SEPARATION

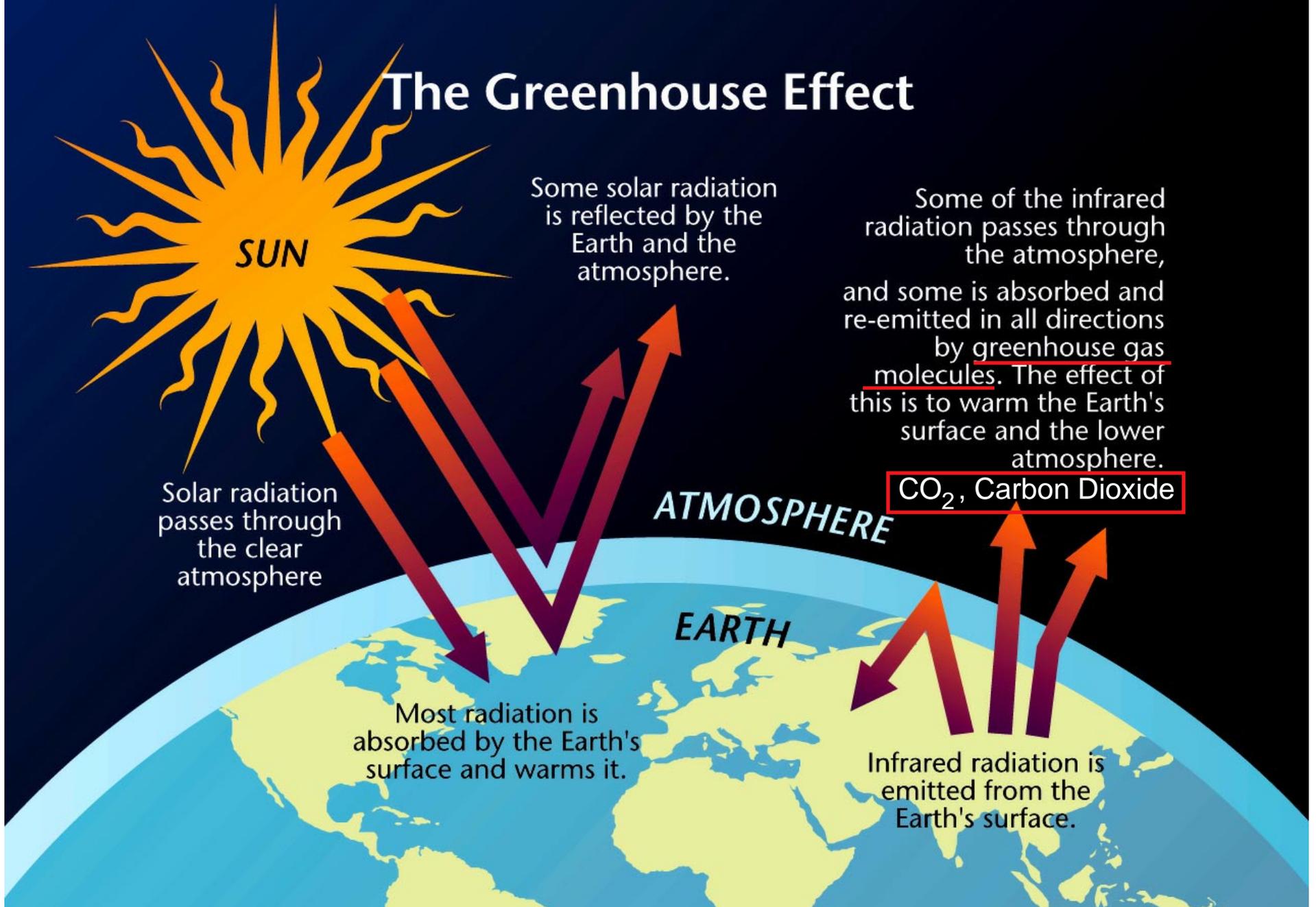


Expected increase equals or exceeds 2 degree threshold.

KEY QUESTION

- How much more CO₂ can be emitted without committing Earth to a temperature increase of 2 °C above preindustrial?

The Greenhouse Effect



ATMOSPHERIC RADIATION

Power per area

Unit:

Watt per square meter

$W m^{-2}$

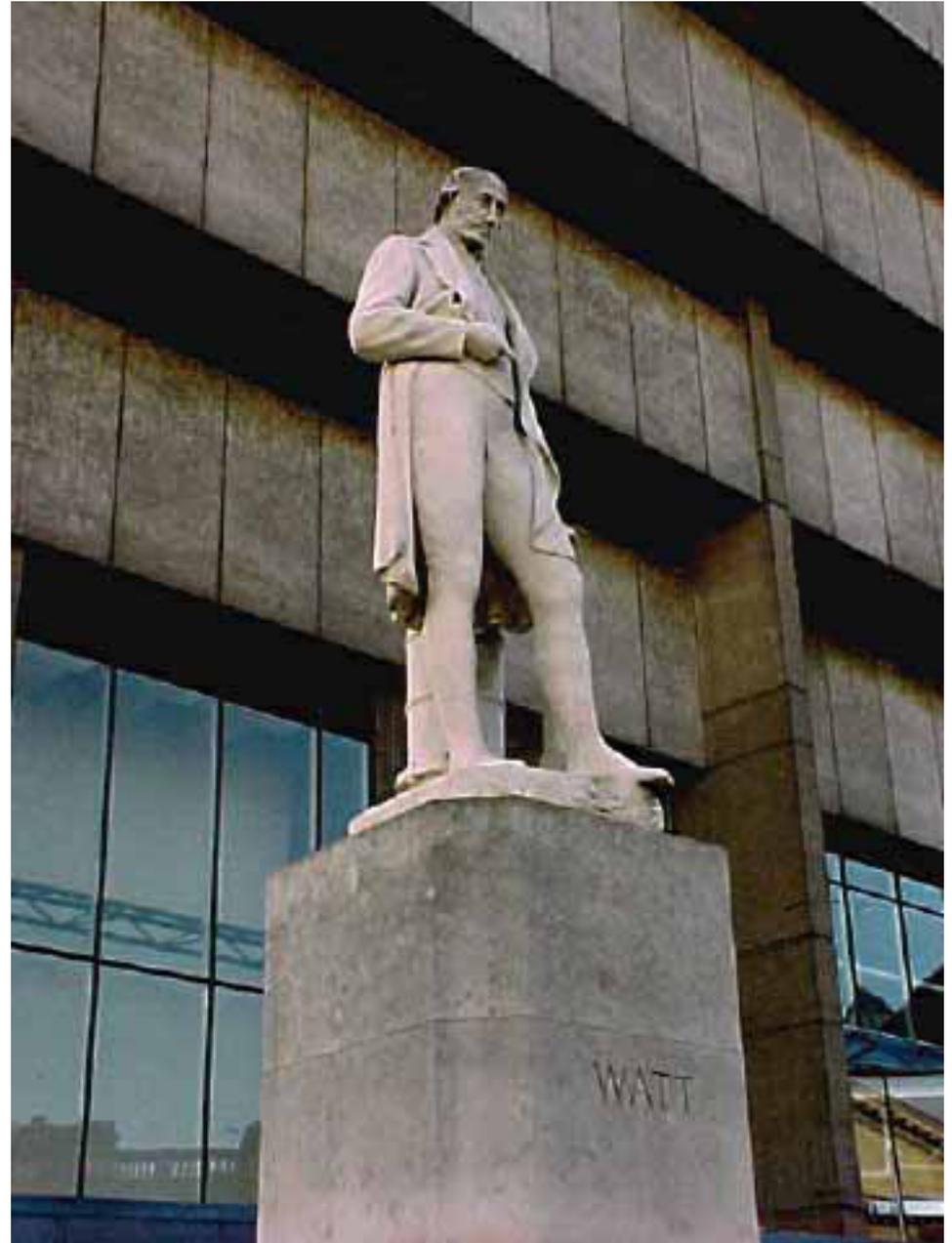
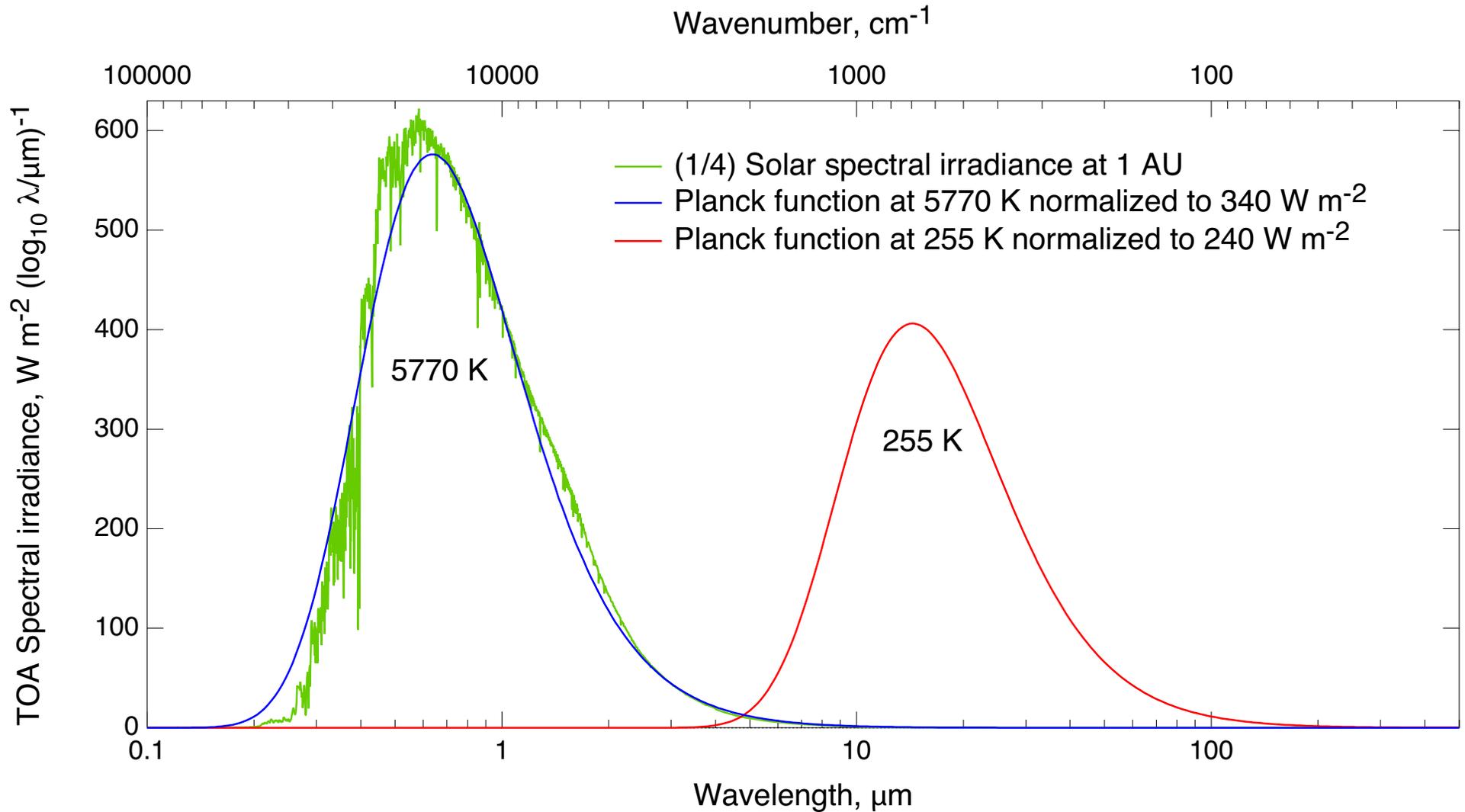


Photo: S. E. Schwartz

THE SOLAR SPECTRUM

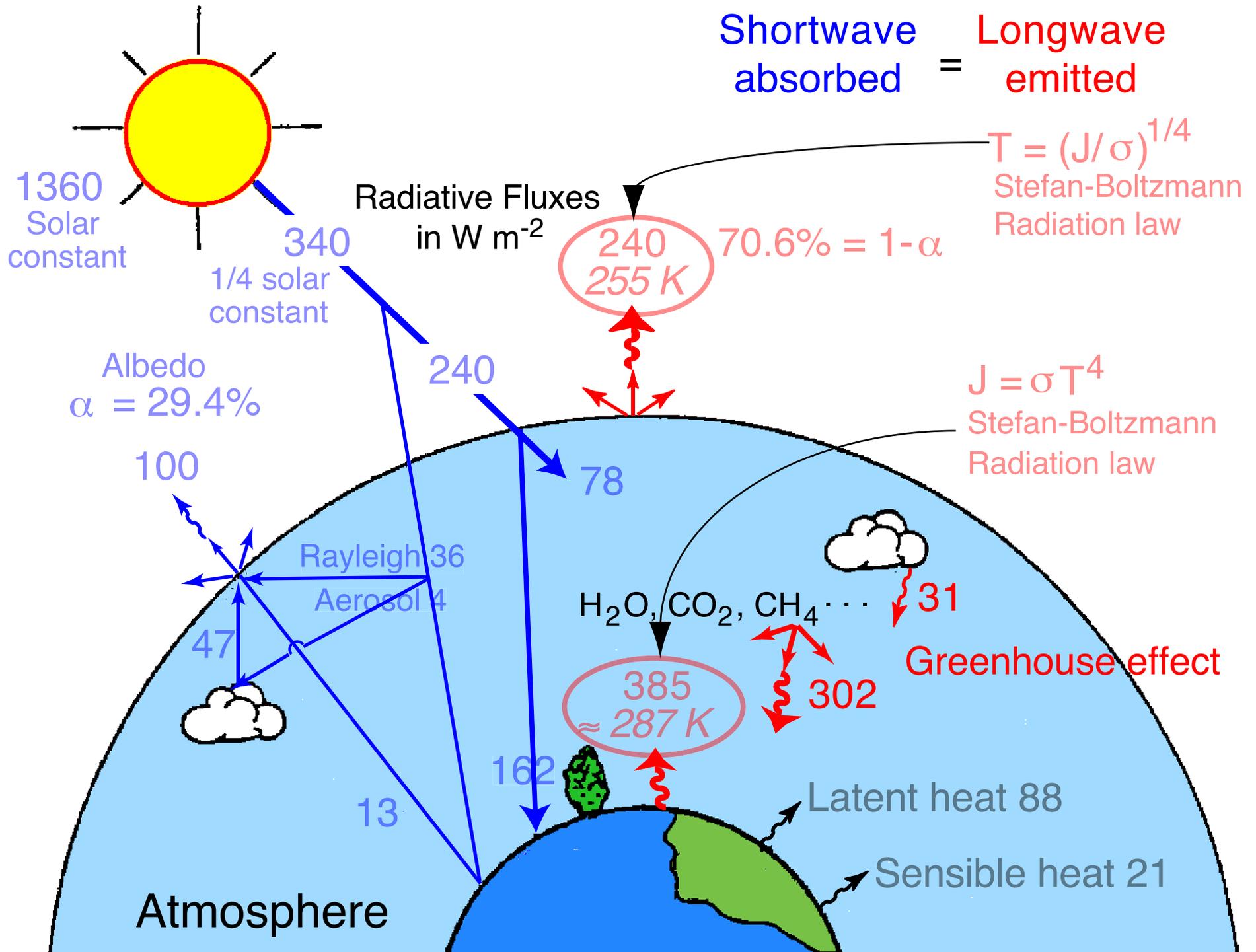
Outside Earth's atmosphere – Compare Planck spectrum at 255 K



Data source: Gueymard, Solar Energy, 2004

Short- and longwave spectra are nearly non-overlapping.

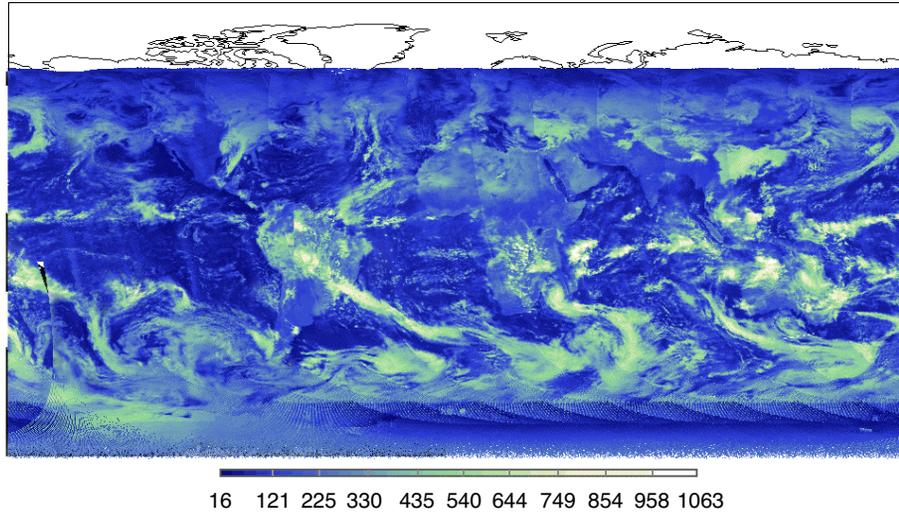
EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



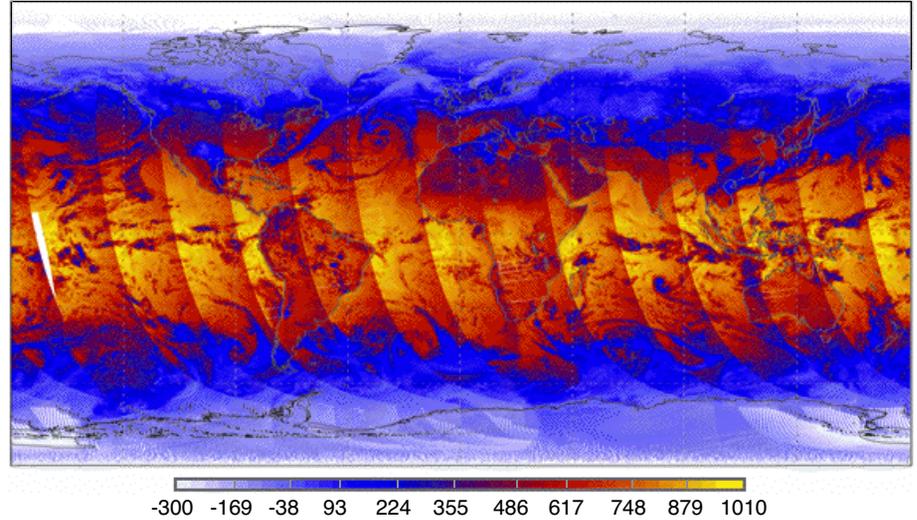
WHAT IT REALLY LOOKS LIKE

Measurements for a single day, March 10, 2012, $W m^{-2}$

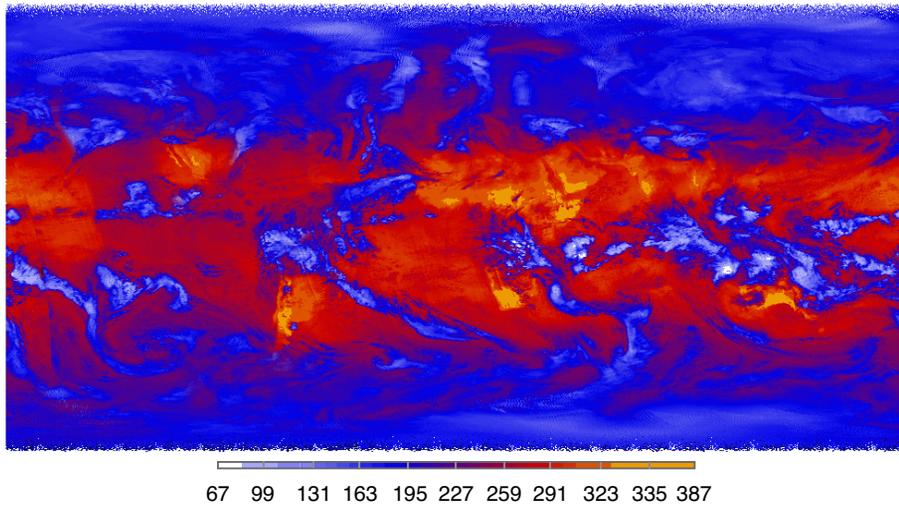
Shortwave upwelling



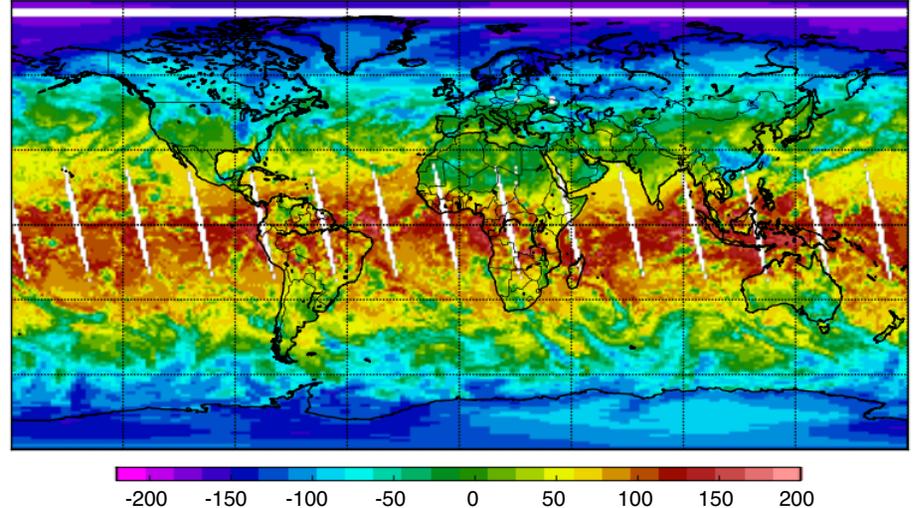
Net daytime, positive downward



Longwave upwelling



Net 24-hr, positive downward



NASA CERES Program, courtesy Norman Loeb

RADIATIVE FORCING

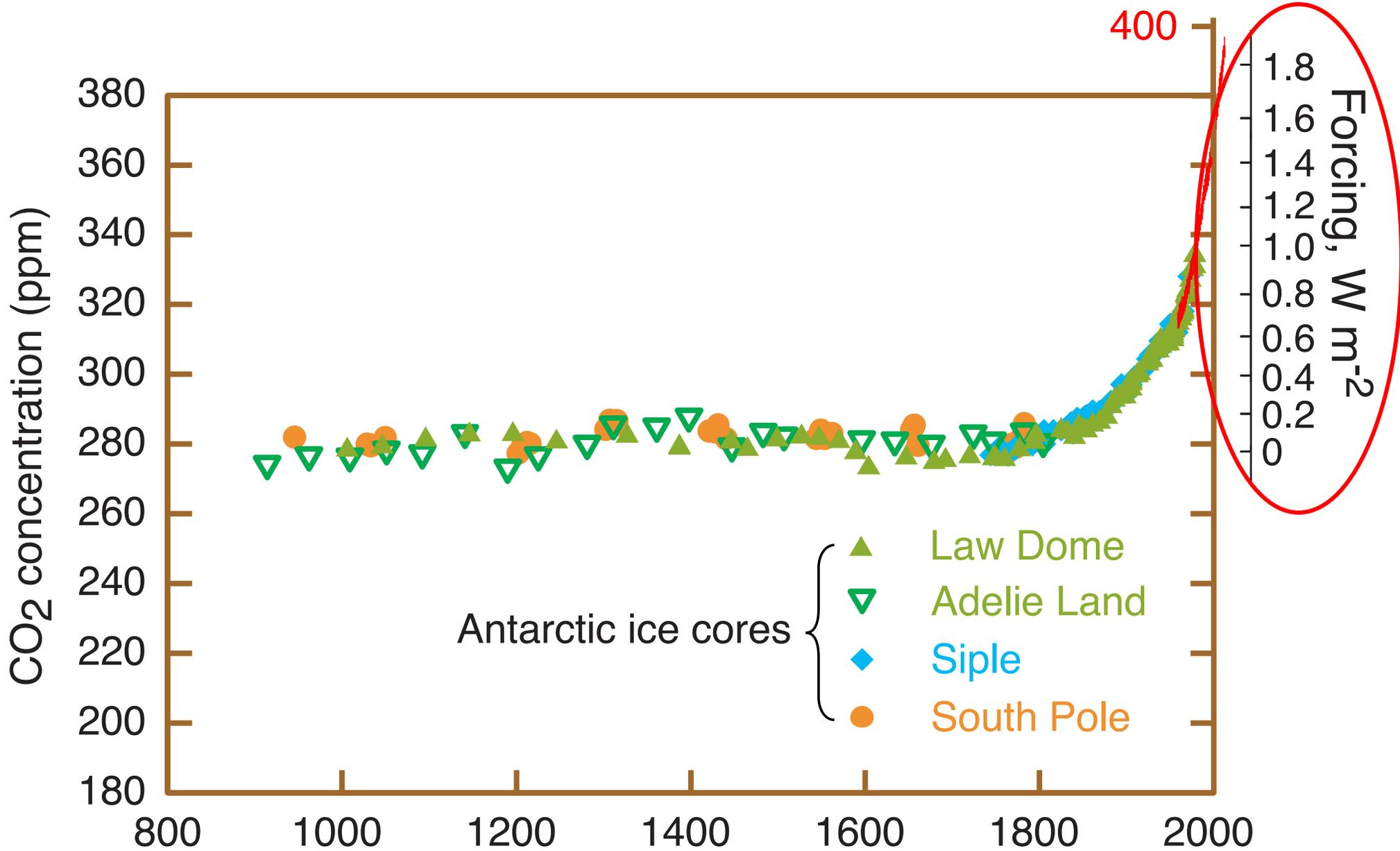
An externally imposed *change* in Earth's radiation budget, W m^{-2} .

Working hypothesis:

Global temperature change is proportional to forcing.

On a global basis radiative forcings are additive and interchangeable.

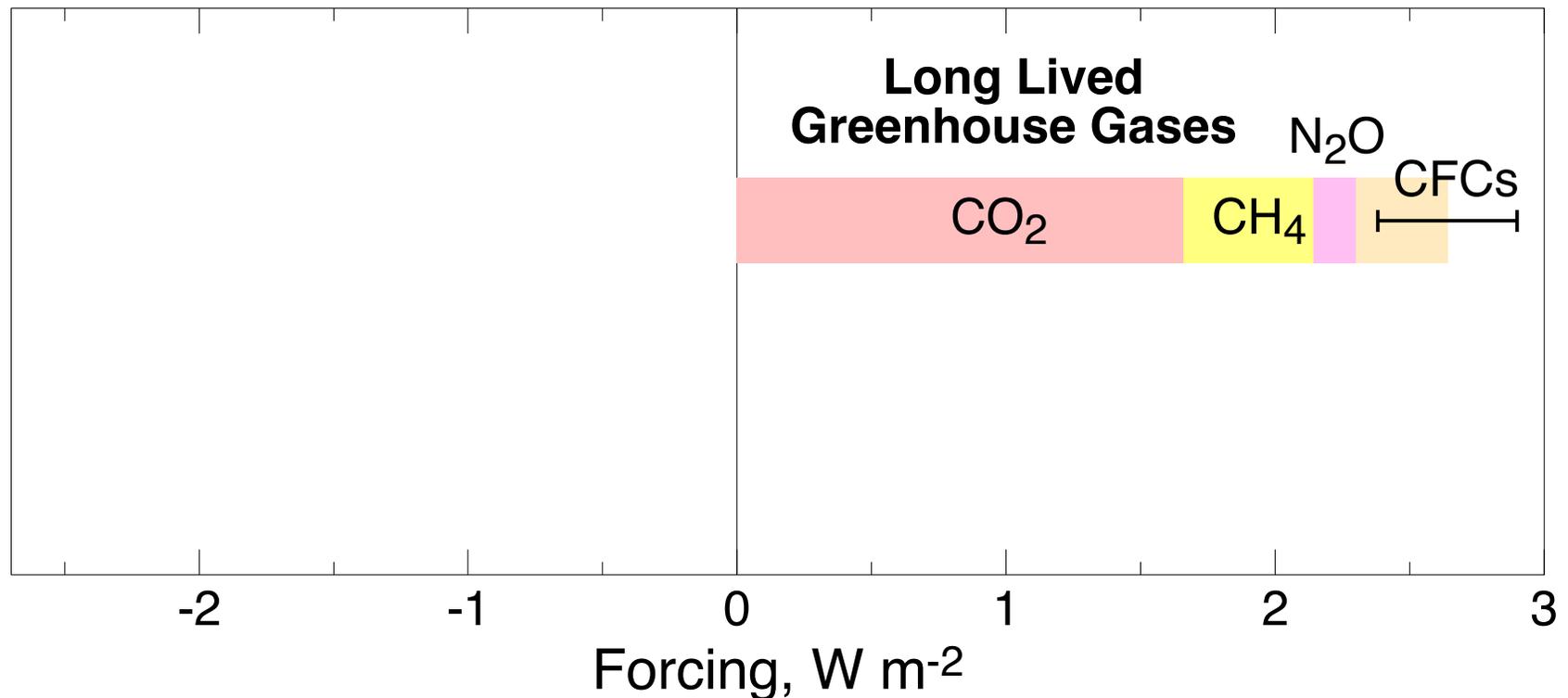
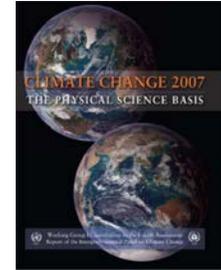
ATMOSPHERIC CARBON DIOXIDE IS INCREASING



Global carbon dioxide concentration over the last thousand years

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

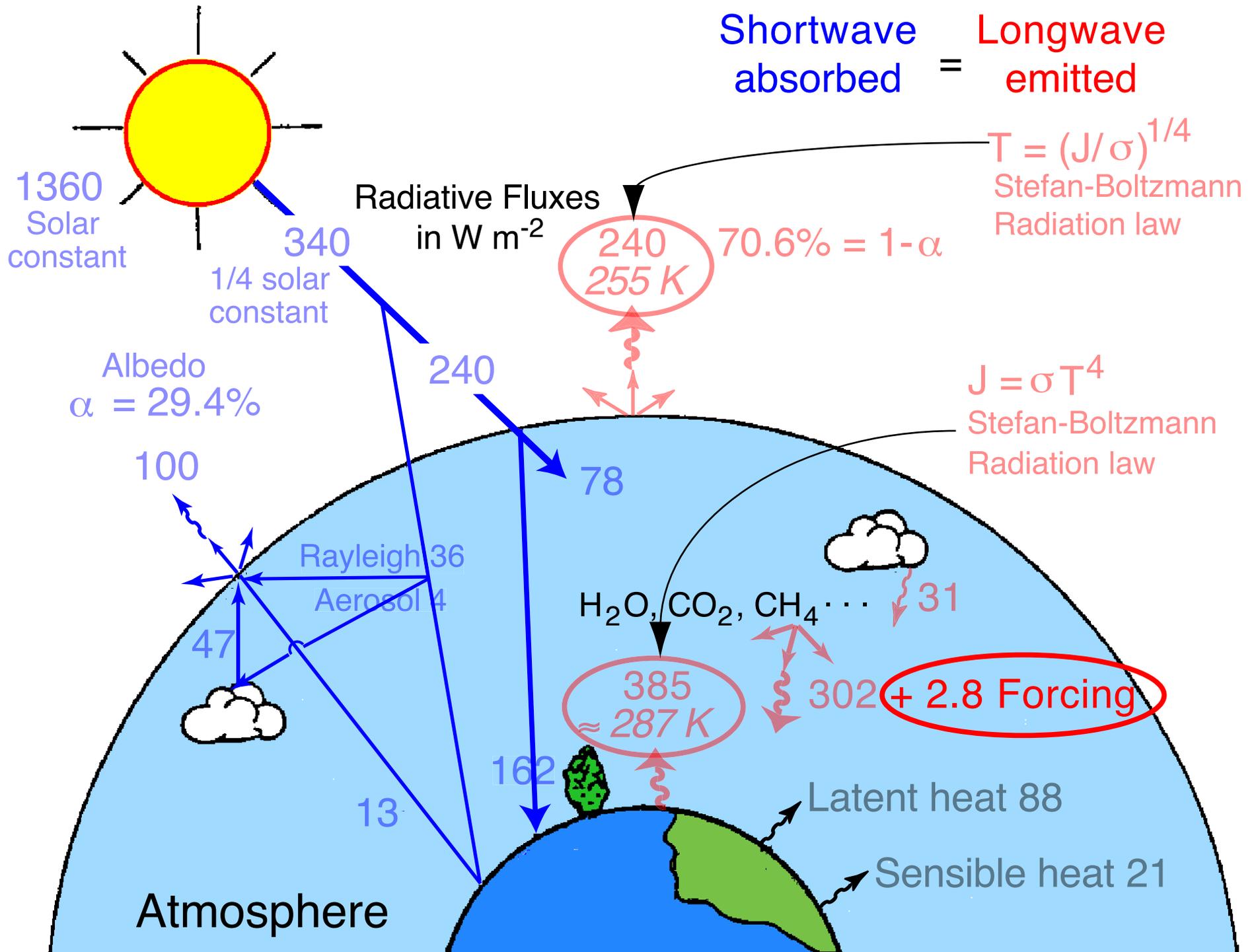
Extracted from IPCC AR4 (2007)



Greenhouse gas forcing is considered accurately known.

Gases are uniformly distributed; radiation transfer is well understood.

EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



HOW MUCH WARMING IS EXPECTED?

Steady-state change
in global mean
surface temperature = Climate
sensitivity \times Forcing

$$\Delta T = S \times F$$

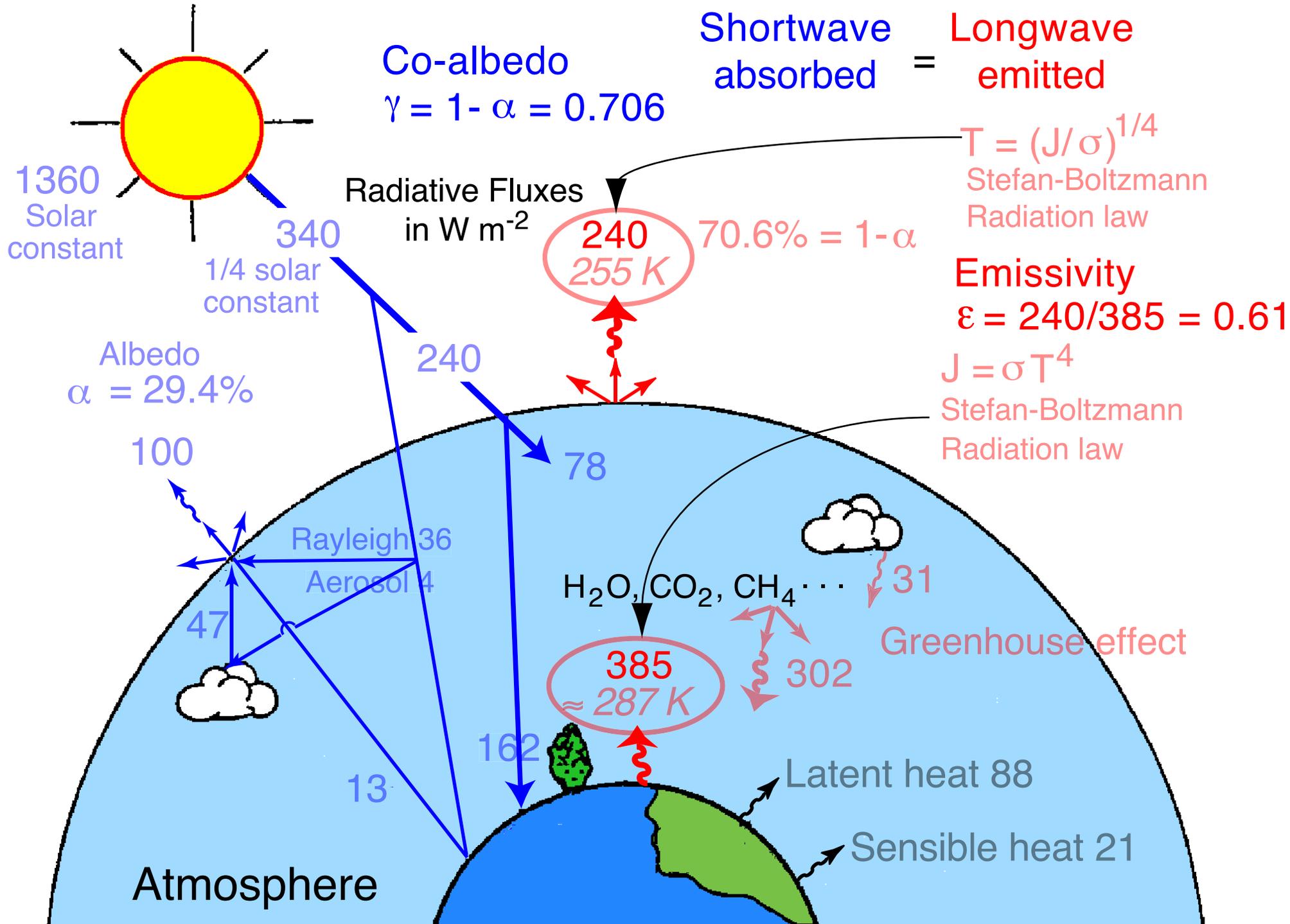
S is “*equilibrium*” sensitivity. Units: K/(W m⁻²)

Sensitivity is commonly expressed as
“CO₂ doubling temperature”

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

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

EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM



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

T_s is global mean surface temperature H is global heat content

Q is absorbed solar energy E is emitted longwave flux

J_S is solar constant γ is planetary co-albedo

σ is Stefan-Boltzmann constant ε is effective emissivity

At radiative uvgcf { 'uvcvg:
$$\frac{\gamma J_S}{4} = \varepsilon \sigma T_s^4$$

$$\gamma = 1 - \alpha \approx 0.7; \quad \varepsilon = \frac{\gamma J_S / 4}{\sigma T_s^4}; \quad \text{for } T_s = 288 \text{ K, } \varepsilon \approx 0.61$$

NO FEEDBACK CLIMATE SENSITIVITY



In absence of feedbacks γ and ε do not depend on T_s

Change in emitted flux per change in temperature:

$$\frac{dE}{dT_s} = \frac{d(\varepsilon\sigma T_s^4)}{dT_s} = 4\varepsilon\sigma T_s^3 = \frac{4}{T_s} E = \frac{4}{T_s} \frac{\gamma J_S}{4} = \frac{\gamma J_S}{T_s}$$

No-feedback sensitivity: $S_{\text{NF}} \equiv \frac{dT_s}{dQ} = \frac{dT_s}{dE} = \left(\frac{dE}{dT_s} \right)^{-1} = \frac{T_s}{\gamma J_S}$

$$J_S = 1360 \text{ Wm}^{-2}; T_s = 287 \text{ K}; \gamma = 0.7;$$

$$S_{\text{NF}} = 0.30 \text{ K / (Wm}^{-2}\text{)}$$

$$\Delta T_{2\times} = F_{2\times} S_{\text{NF}} = 3.7 \text{ Wm}^{-2} \times 0.30 \text{ K / (Wm}^{-2}\text{)} = 1.1 \text{ K}$$

Water Vapor Feedback: Pretty Well Understood

Higher temperature,
More water vapor.
More infrared
is absorbed



Positive Feedback
Higher Sensitivity

Cloud Feedbacks: A Big Mystery in Climate Sensitivity

Higher temperature,
Clouds evaporate.
More sunlight
is absorbed



Positive Feedback
Higher Sensitivity

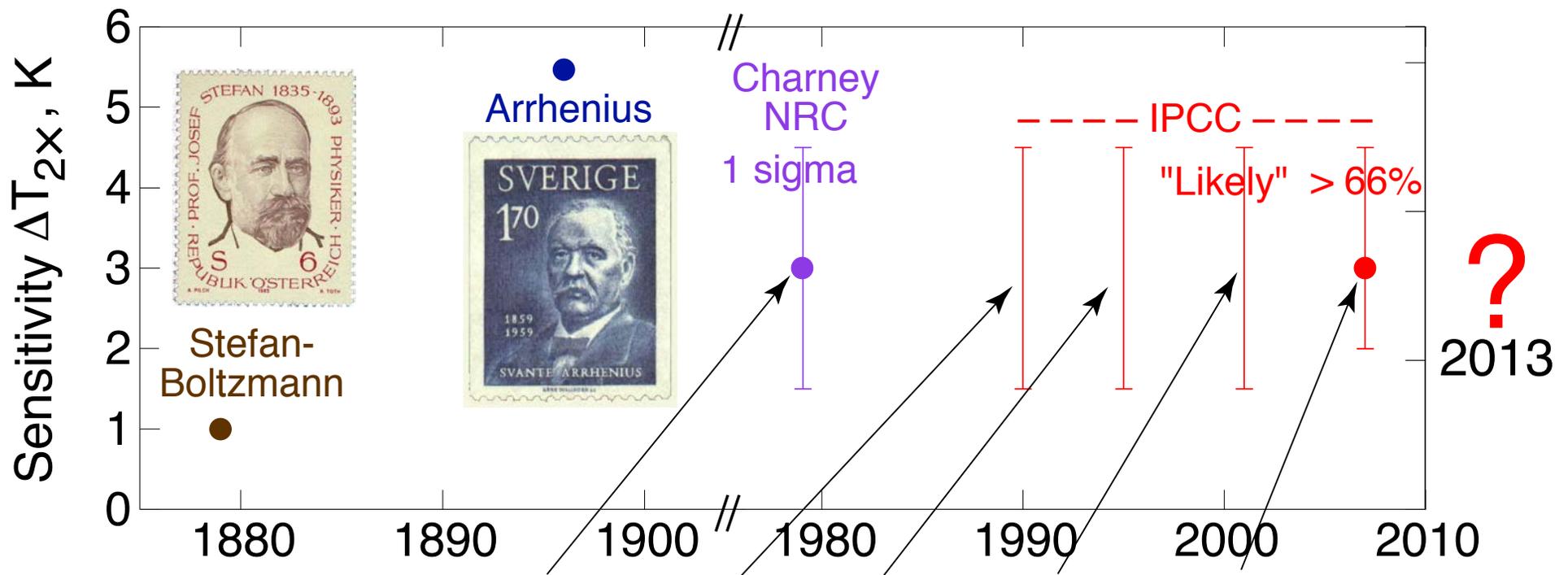
Higher temperature,
More water vapor,
More clouds.
Less sunlight is
absorbed



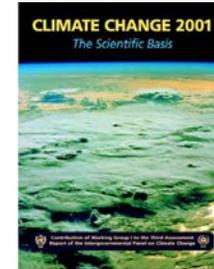
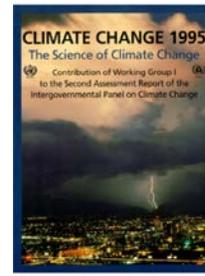
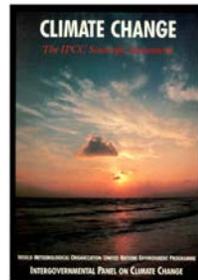
Negative Feedback
Lower Sensitivity

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

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



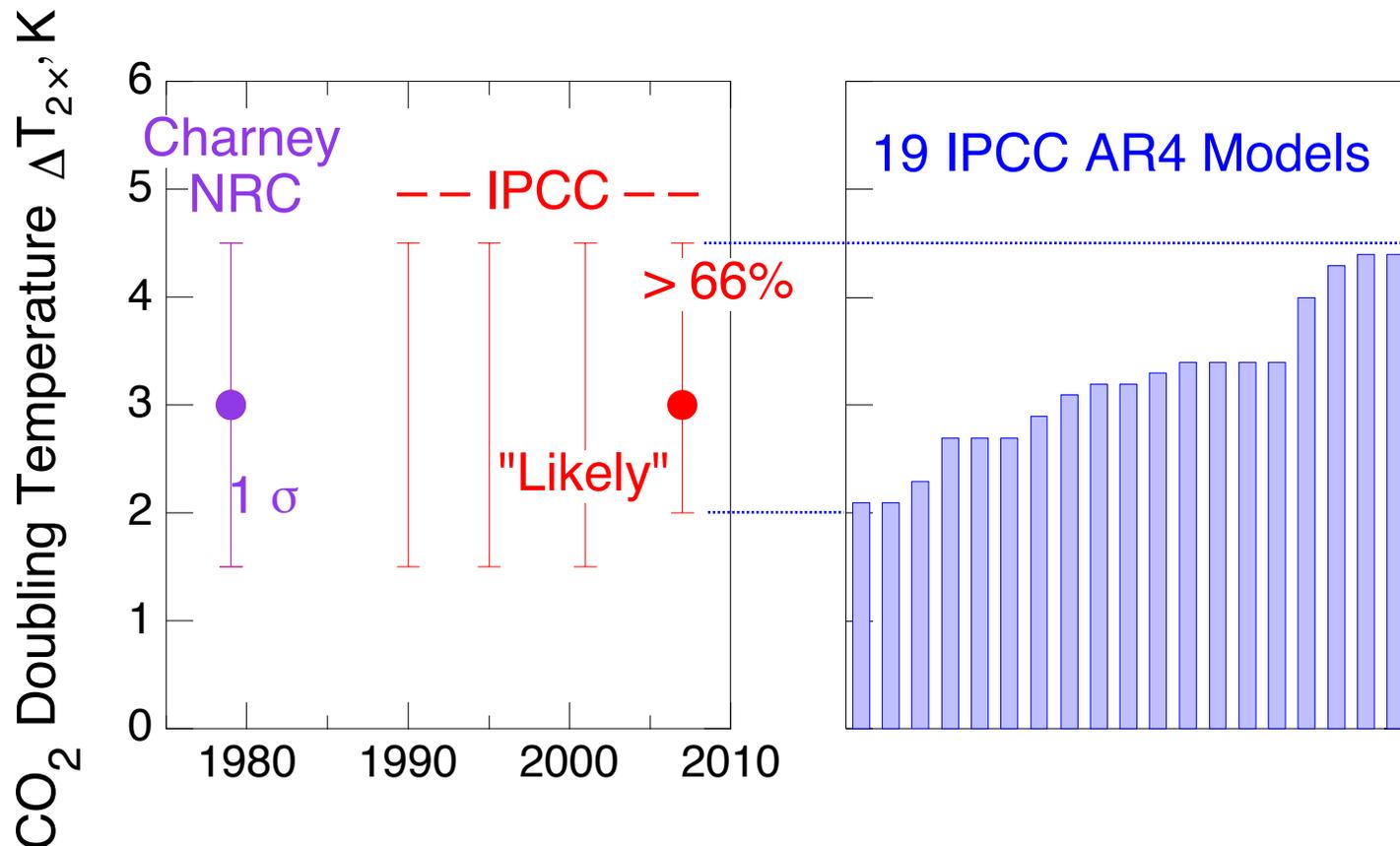
**Carbon Dioxide and Climate:
A Scientific Assessment**
NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979



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

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.

?? QUESTION ??

- Why is there such a large range of sensitivities in current climate models and why hasn't this situation improved much in thirty years?

ANSWER

- This is a really tough scientific problem!

A REALLY TOUGH SCIENTIFIC PROBLEM

- Determine the consequences of a systematic change of less than 1% in a quantity that is highly variable in time and space applied to a noisy dynamic system.
- Right now we do not even know the *sign* of how much more CO₂ can be added to the atmosphere without committing Earth to a temperature increase $\geq 2^\circ$ C.
- Even at the low end of the climate sensitivity range, expected temperature increase from long-lived greenhouse gases $\sim 1.4^\circ$ C, the consequences would be severe.
- Why has Earth *not* warmed up the expected amount, 1.4 to 3.2 $^\circ$ C? We don't know, but that's another lecture.