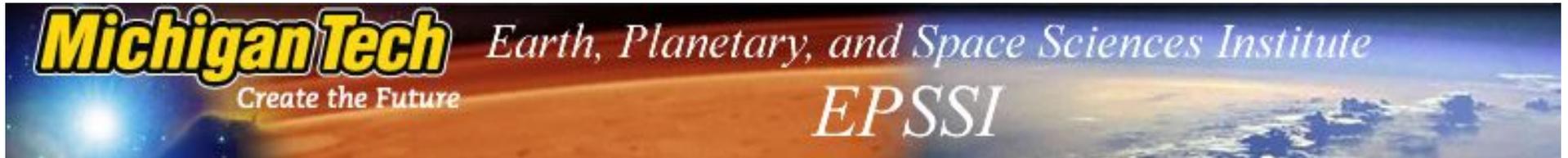


WHY HAS EARTH **NOT** WARMED  
AS MUCH AS EXPECTED?  
AND WHY IS THIS SO IMPORTANT?

Stephen E. Schwartz

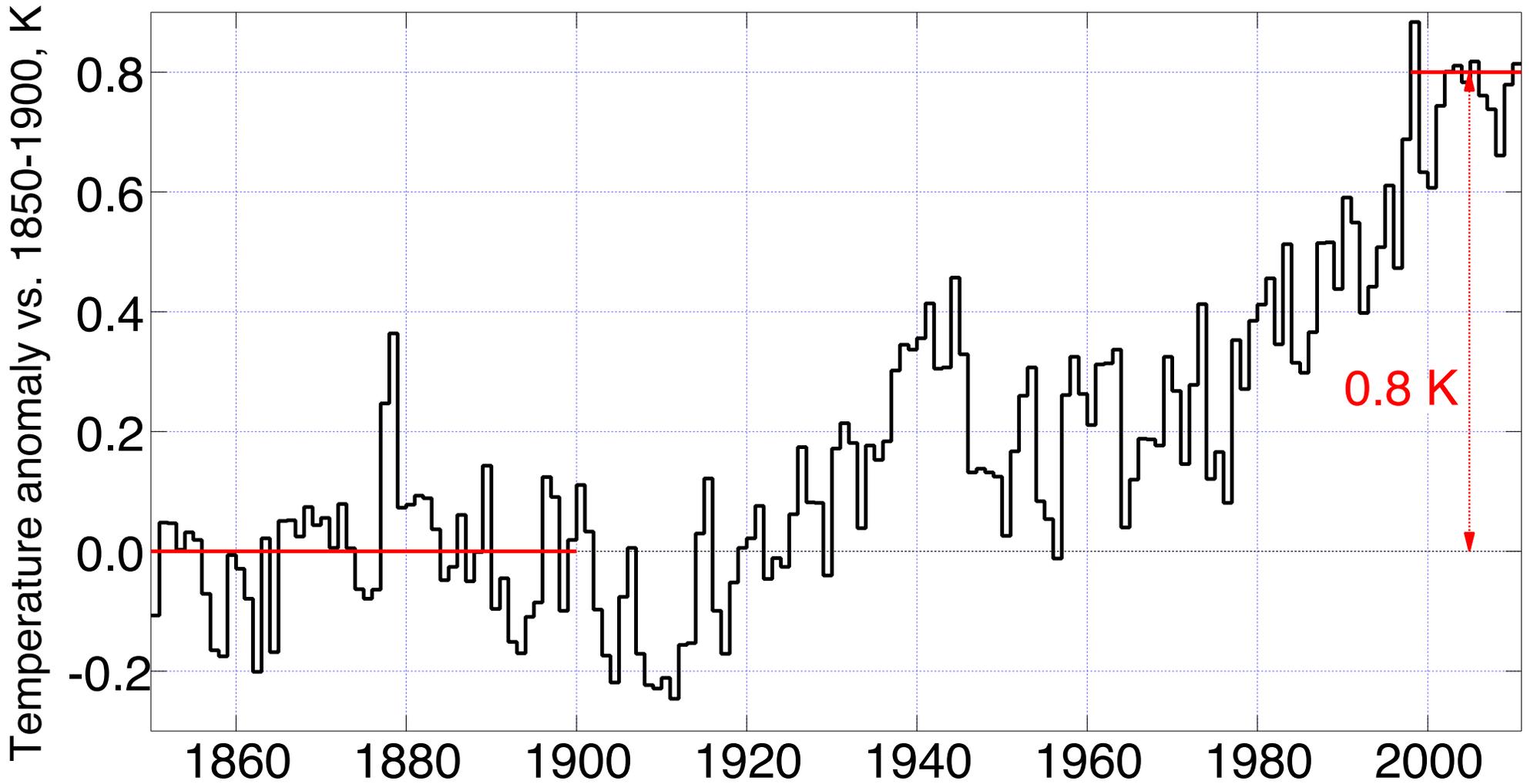
**BROOKHAVEN**  
NATIONAL LABORATORY  
Upton NY USA



Houghton, MI  
October 7, 2013

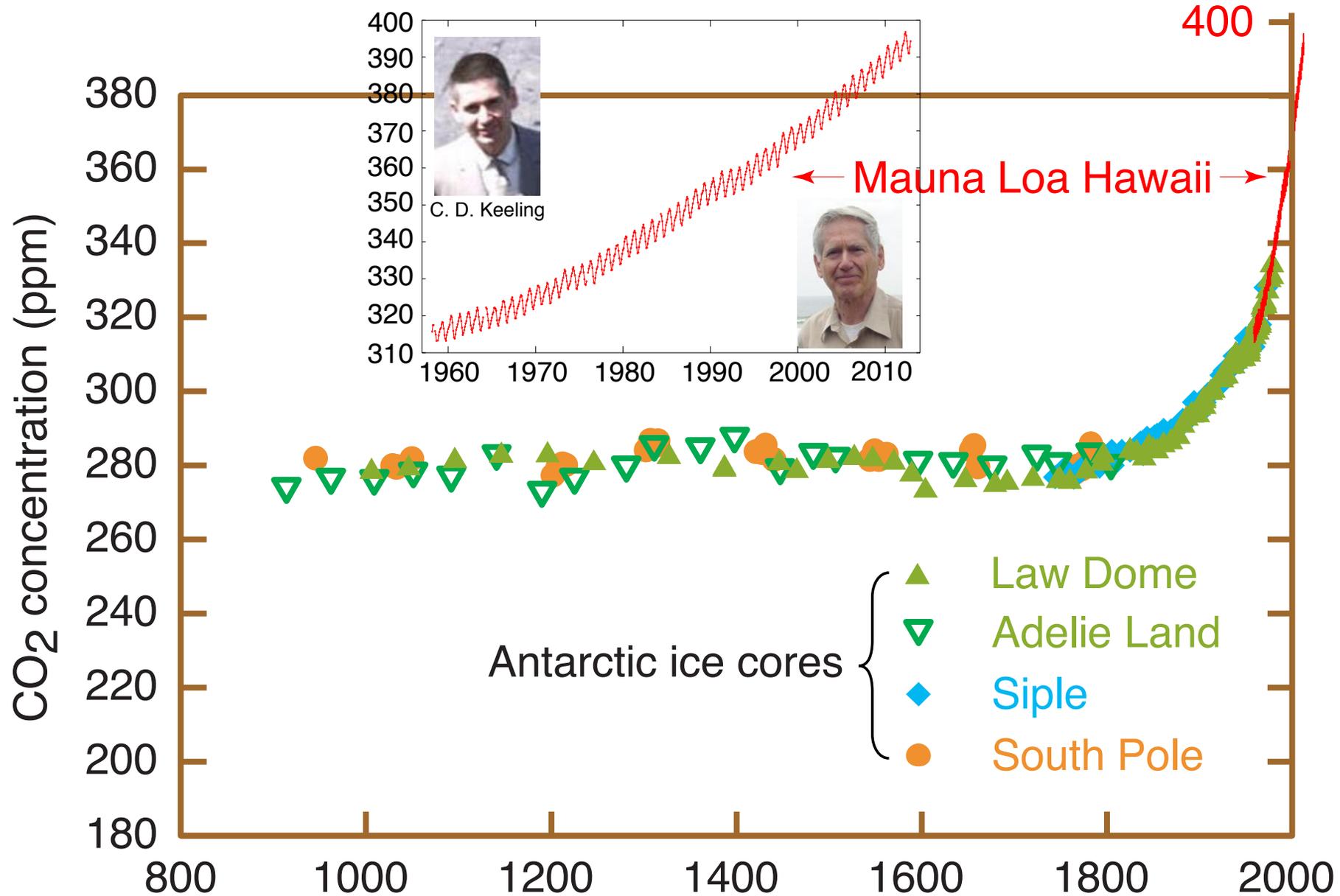
[www.ecd.bnl.gov/steve](http://www.ecd.bnl.gov/steve)

# GLOBAL TEMPERATURE CHANGE SINCE 1850



*Climatic Research Unit, East Anglia, UK*

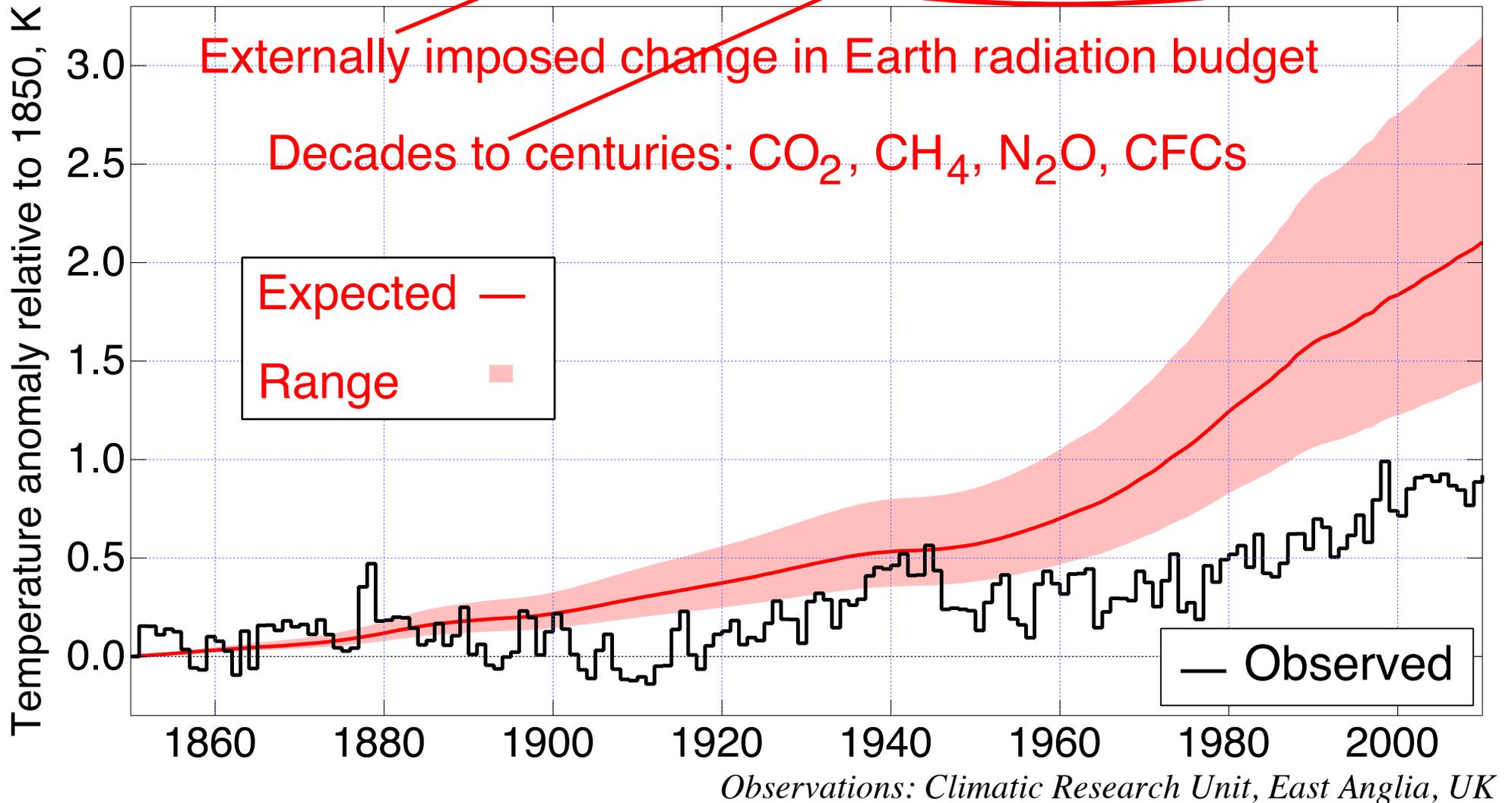
# ATMOSPHERIC CARBON DIOXIDE IS INCREASING



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

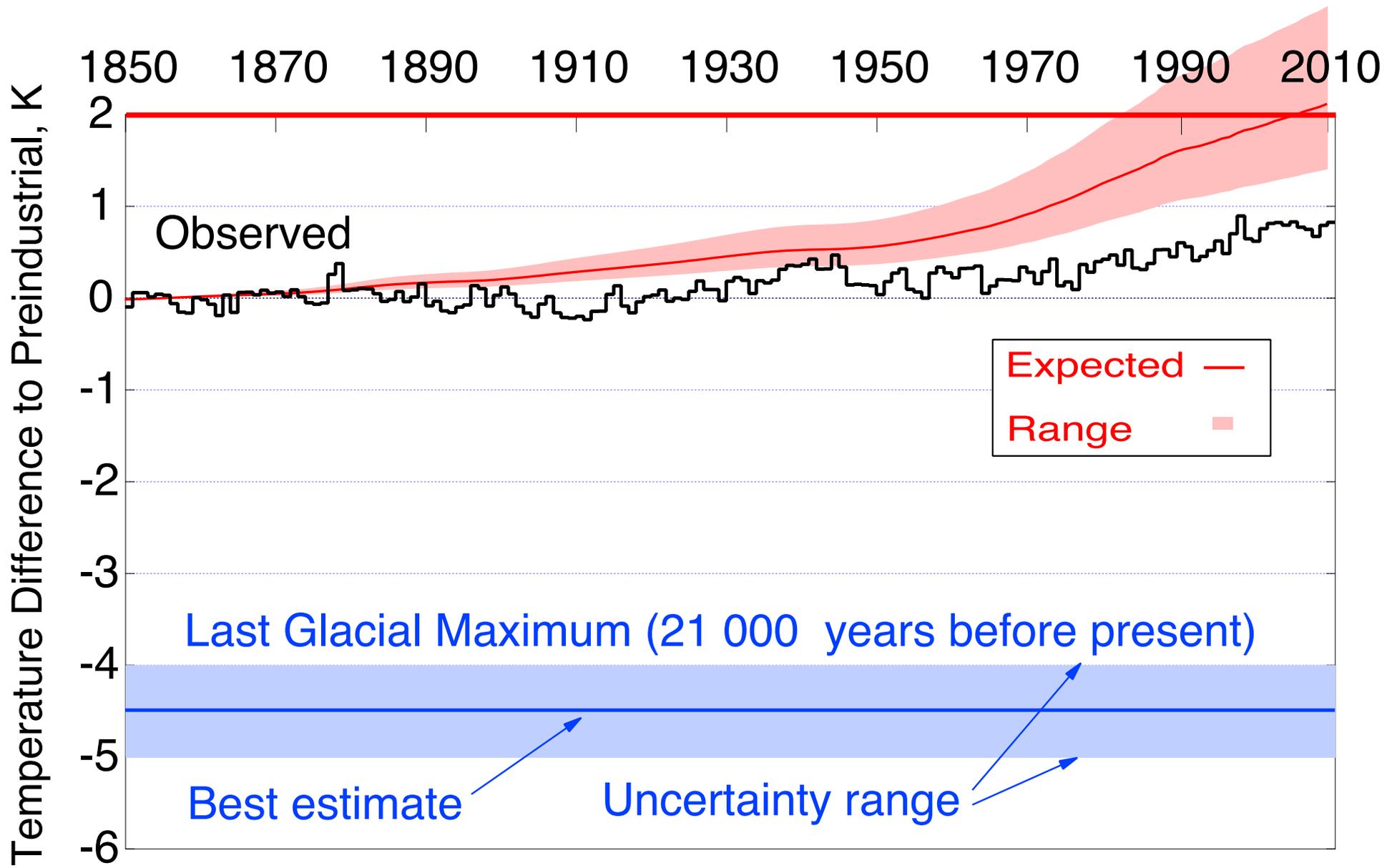
The Heads of State, Heads of Government, Ministers . . . present at the United Nations Climate Change Conference 2009 in Copenhagen:

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

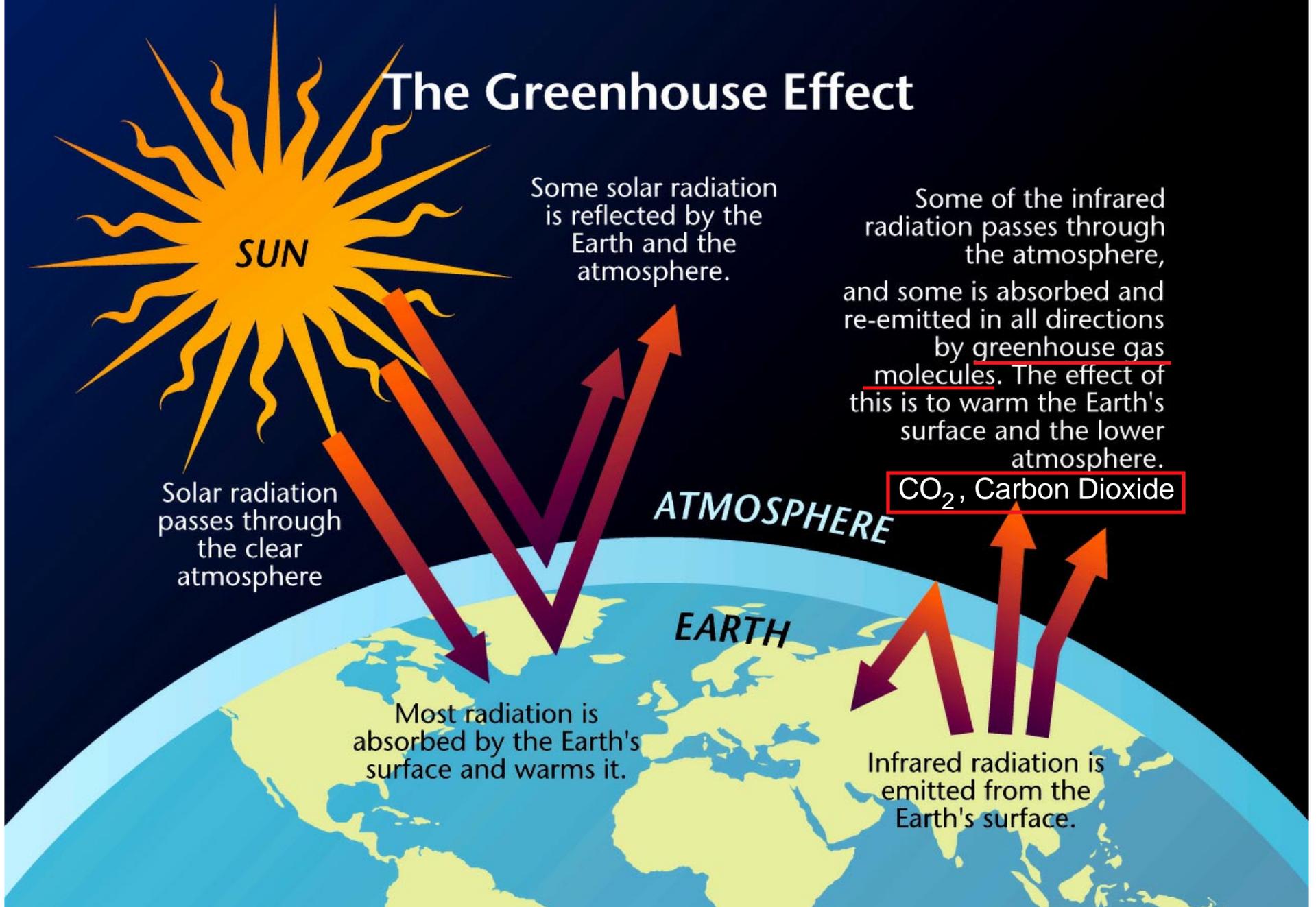


Expected increase equals or exceeds 2 degree threshold.

# KEY QUESTION

- How much more CO<sub>2</sub> can be emitted without committing Earth to a temperature increase of 2 °C above preindustrial?

# The Greenhouse Effect



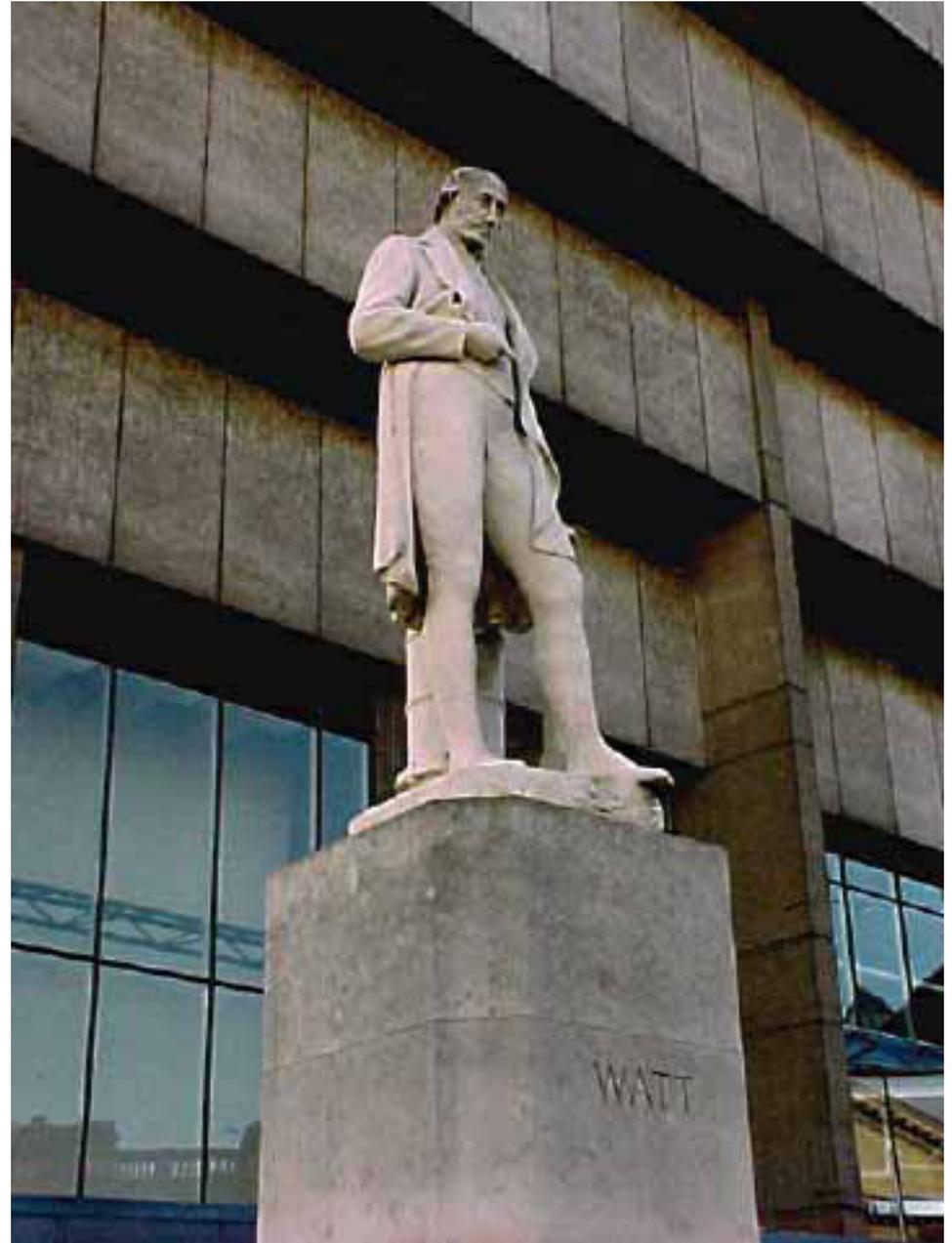
# ***ATMOSPHERIC RADIATION***

*Power per area*

*Unit:*

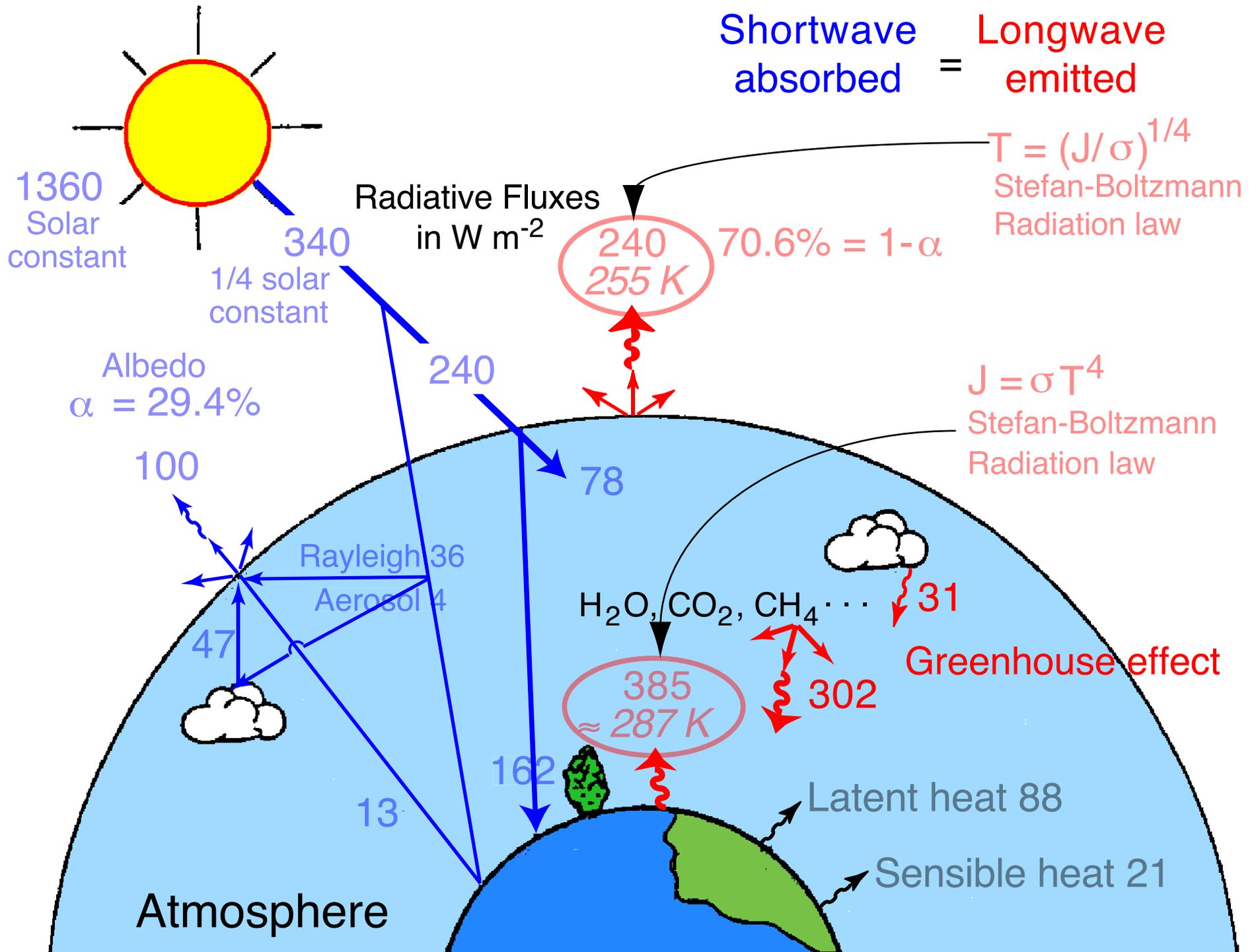
*Watt per square meter*

*$W m^{-2}$*



*Photo: S. E. Schwartz*

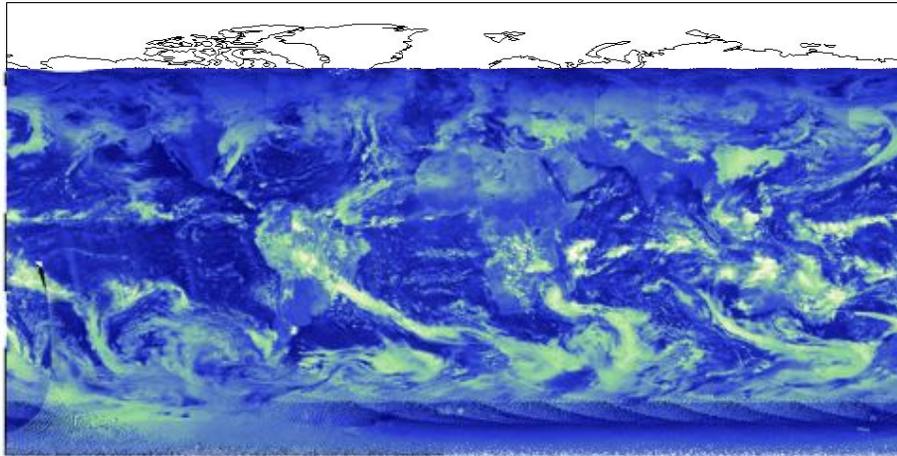
# EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



# WHAT IT REALLY LOOKS LIKE

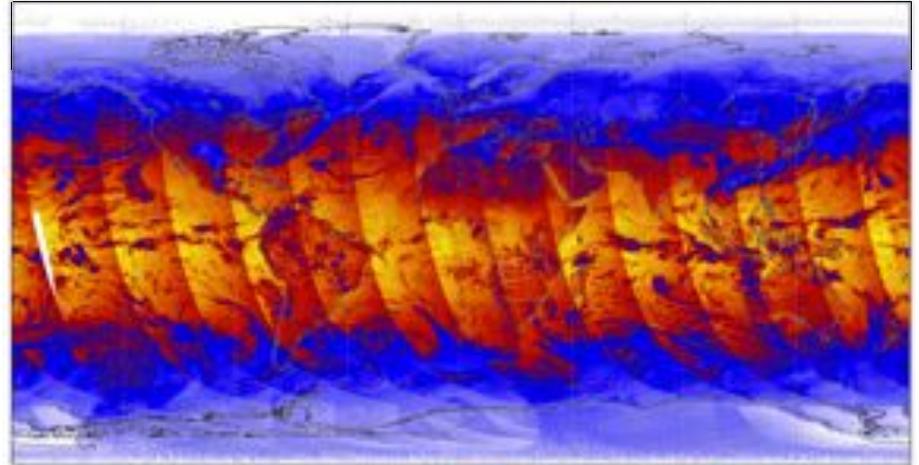
Measurements for a single day, March 10, 2012,  $W m^{-2}$

Shortwave upwelling



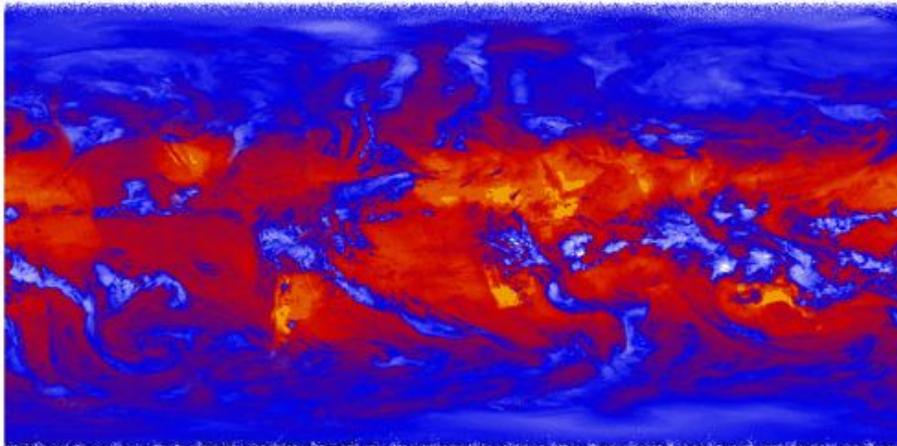
16 121 225 330 435 540 644 749 854 958 1063

Net daytime, positive downward



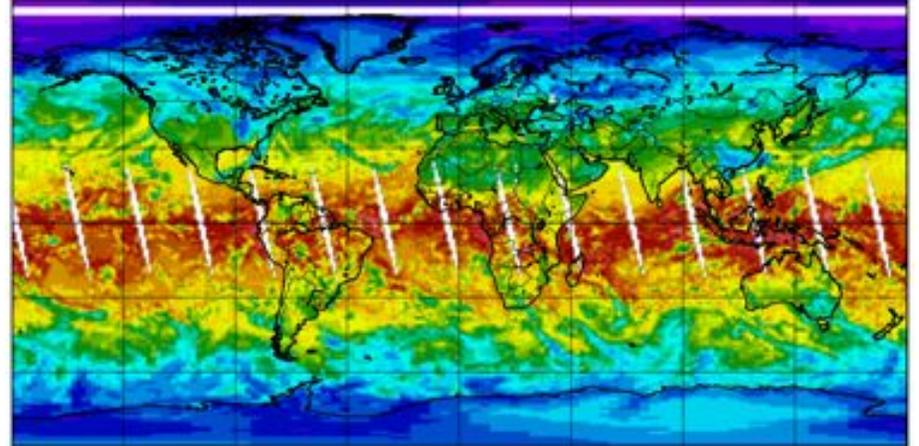
-300 -169 -38 93 224 355 486 617 748 879 1010

Longwave upwelling



67 99 131 163 195 227 259 291 323 335 387

Net 24-hr, positive downward



-200 -150 -100 -50 0 50 100 150 200

*NASA CERES Program, courtesy Norman Loeb*

# ***RADIATIVE FORCING***

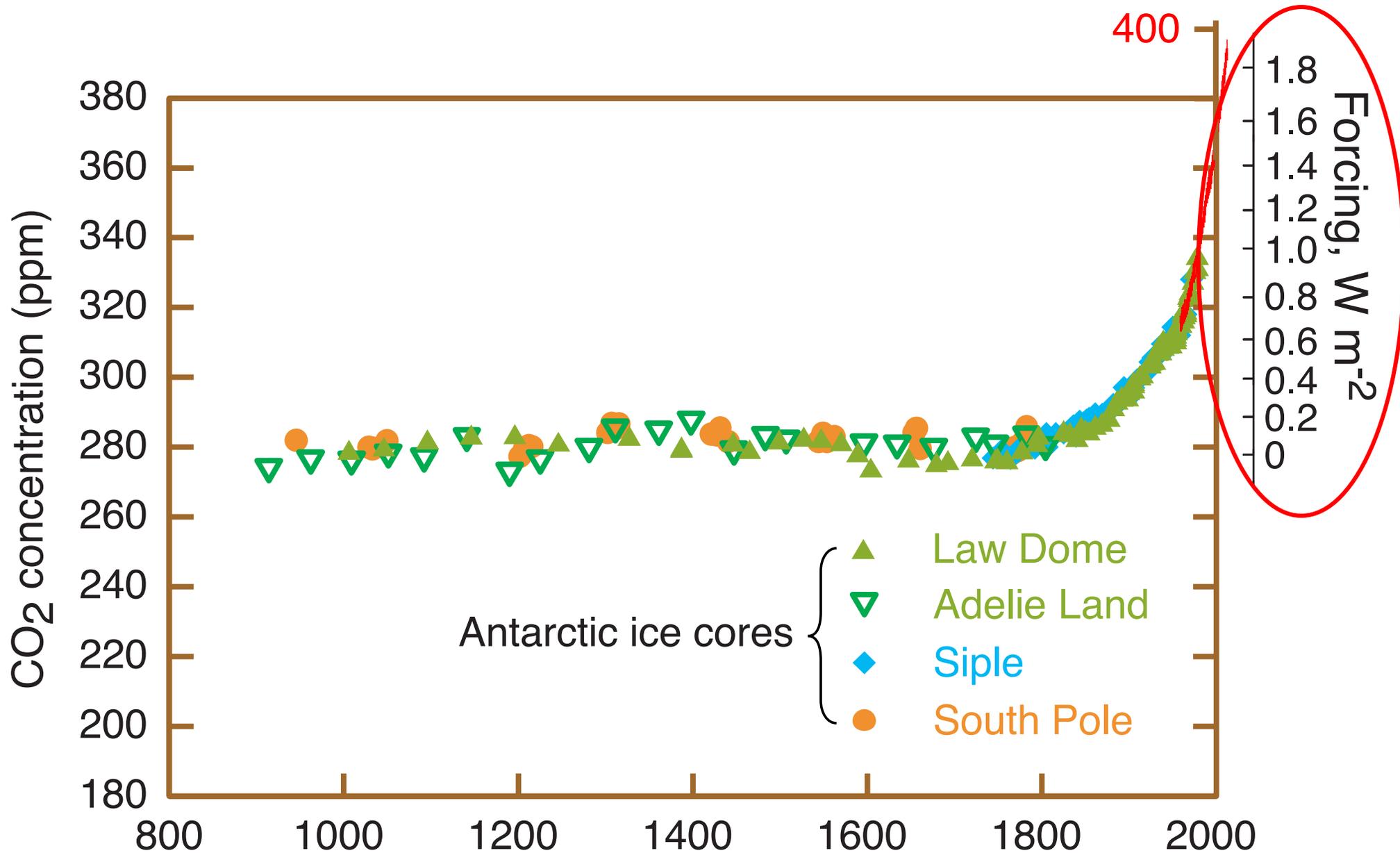
An externally imposed *change* in Earth's radiation budget,  $\text{W m}^{-2}$ .

*Working hypothesis:*

*Global temperature change is proportional to forcing.*

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

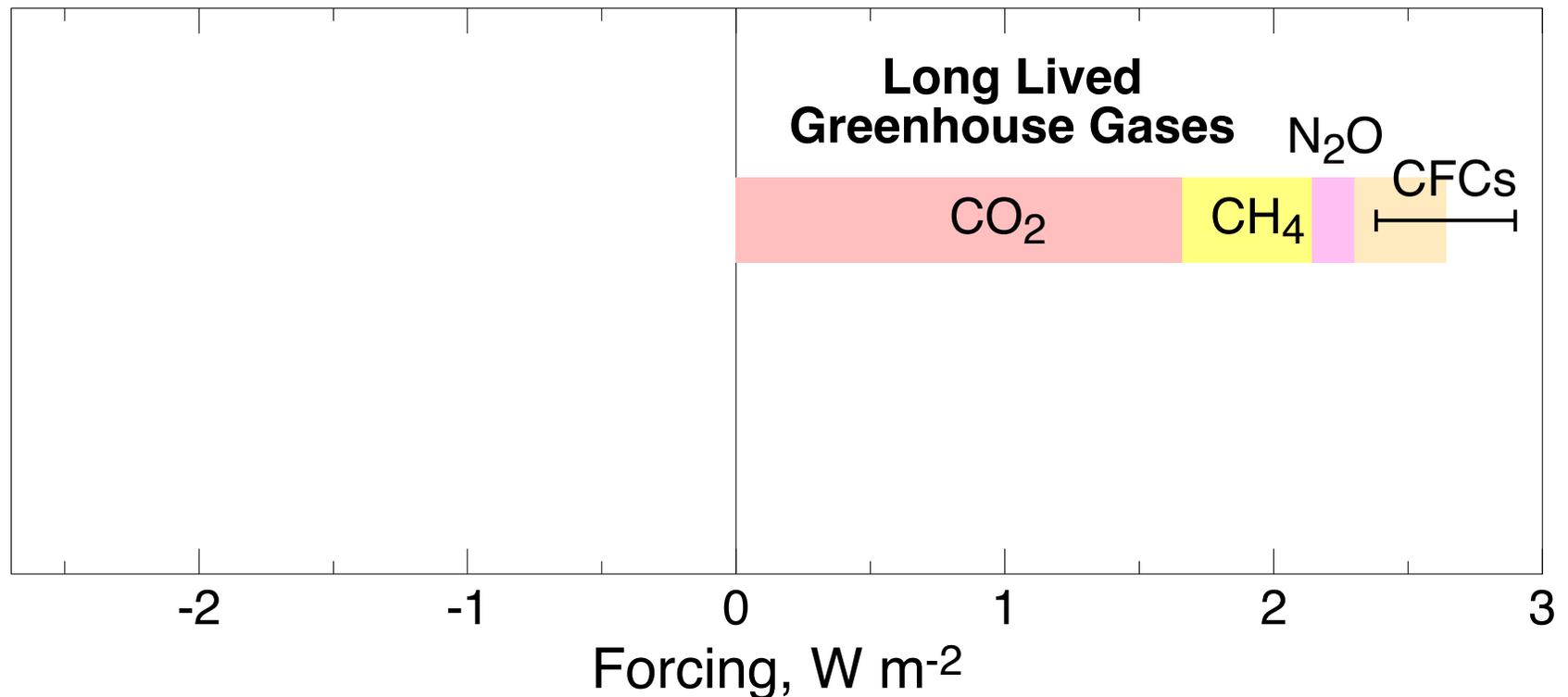
# ATMOSPHERIC CARBON DIOXIDE IS INCREASING



Global carbon dioxide concentration over the last thousand years

# CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

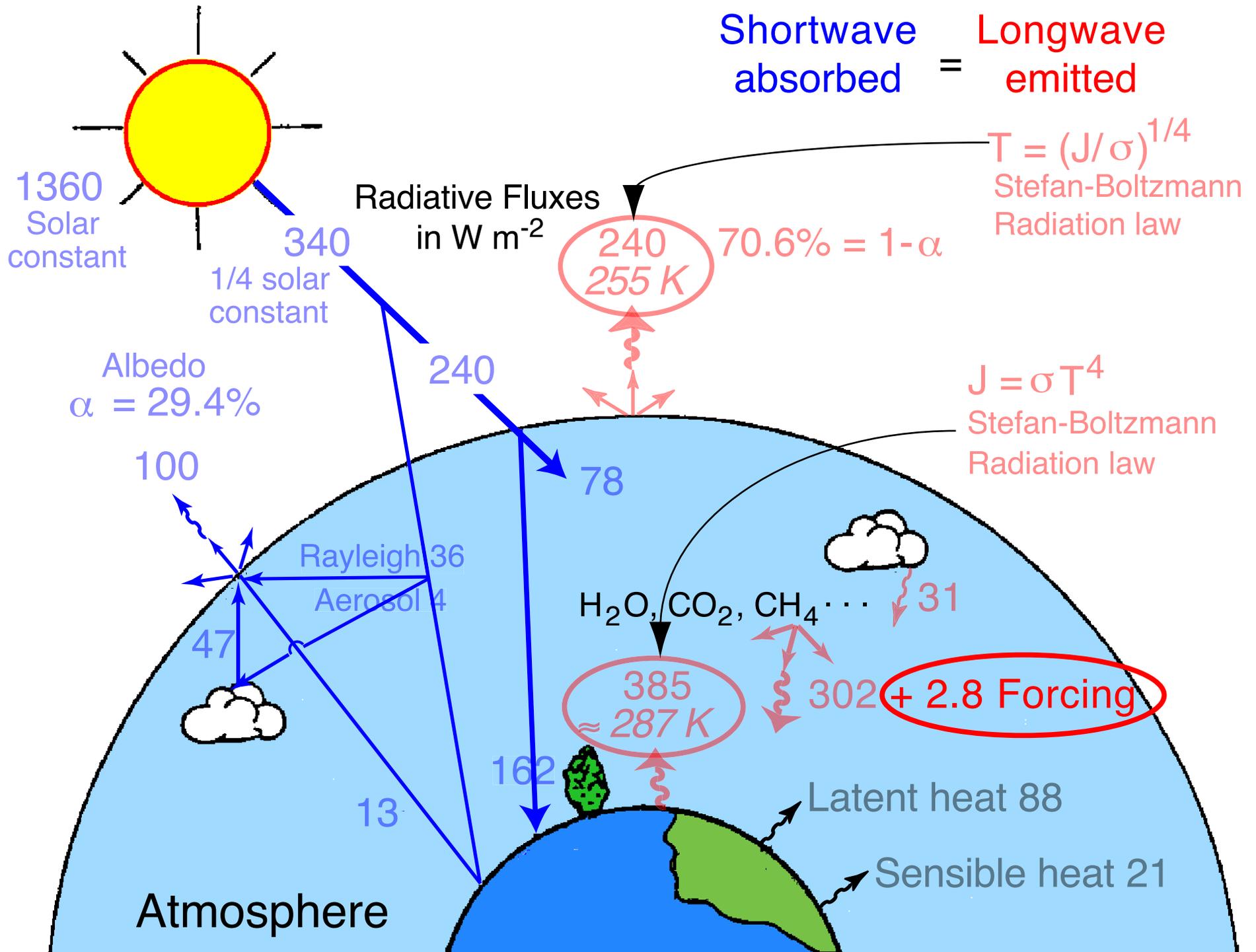
Extracted from IPCC AR4 (2007)



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

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

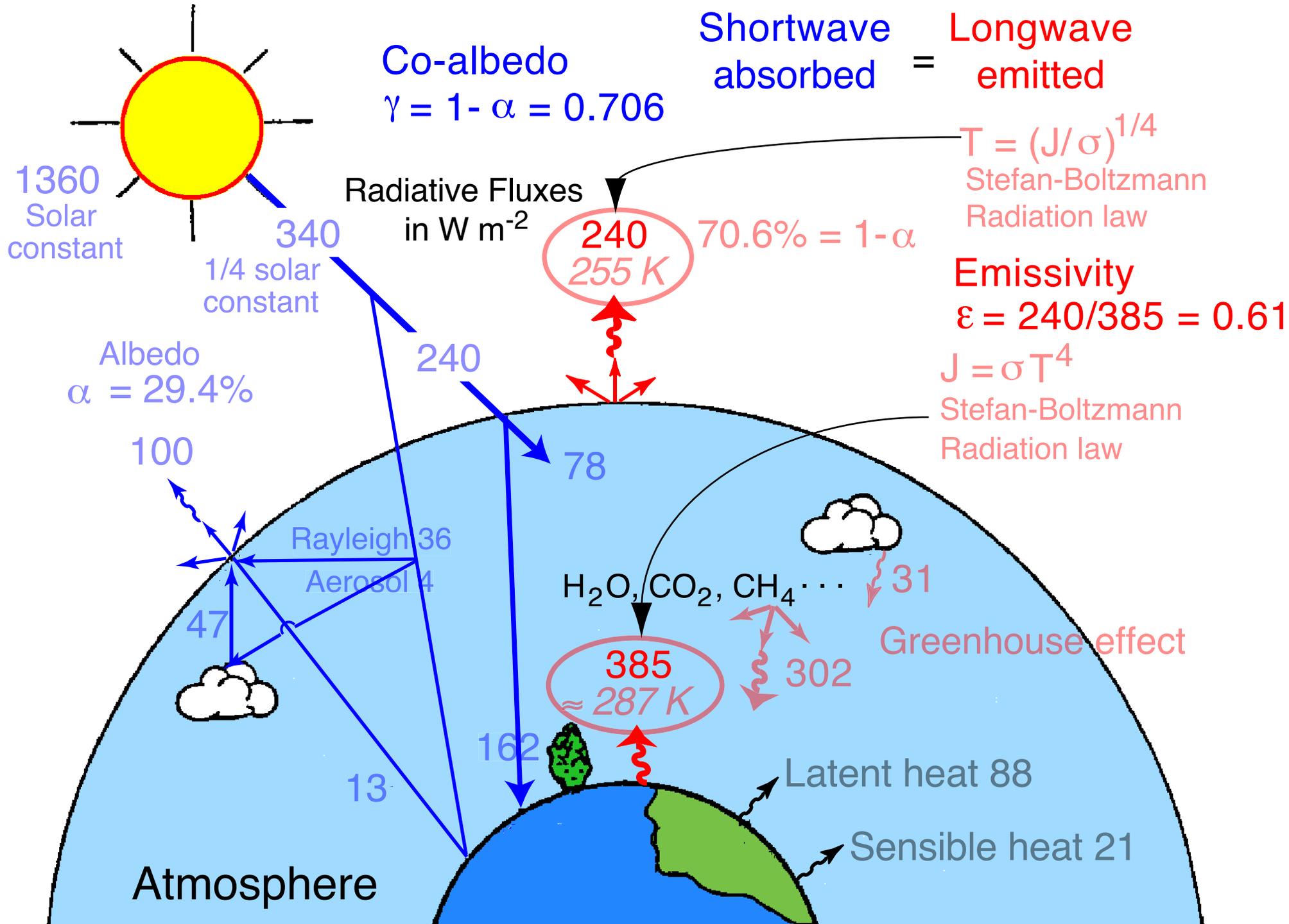
$S$  is “*equilibrium*” sensitivity. Units: K/(W m<sup>-2</sup>)

Sensitivity is commonly expressed as  
“CO<sub>2</sub> doubling temperature”

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

where  $F_{2\times}$  is the “CO<sub>2</sub> doubling forcing” *ca.* 3.7 W m<sup>-2</sup>.

# 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       $\gamma$  is planetary co-albedo

$\sigma$  is Stefan-Boltzmann constant       $\varepsilon$  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*  $\gamma$  and  $\varepsilon$  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:  $S_{\text{NF}} \equiv \frac{dT_s}{dQ} = \frac{dT_s}{dE} = \left( \frac{dE}{dT_s} \right)^{-1} = \frac{T_s}{\gamma J_S}$

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

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

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

**~1%**

**~0.3%**

# 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

# Cloud Feedbacks: A Big Mystery in Climate Sensitivity

Higher temperature,  
Clouds evaporate.  
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Positive Feedback  
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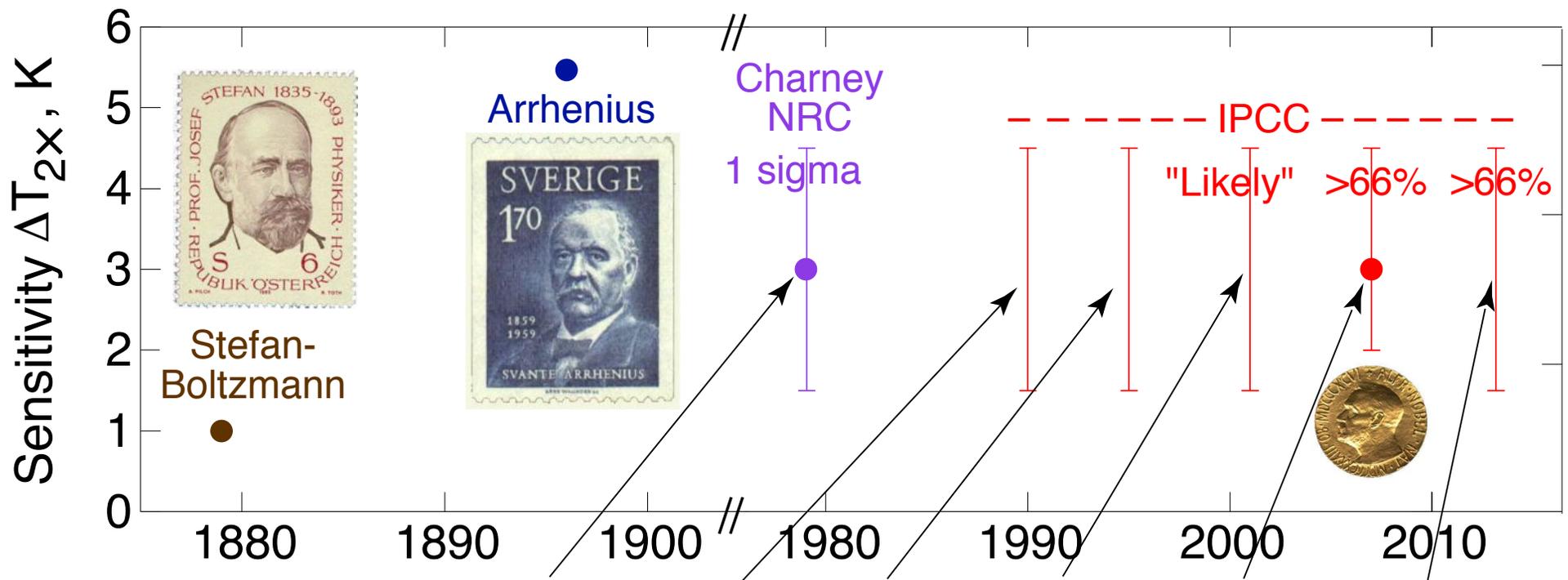
Higher temperature,  
More water vapor,  
More clouds.  
Less sunlight is  
absorbed



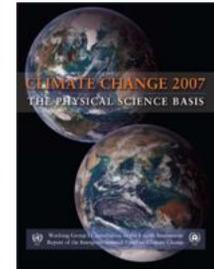
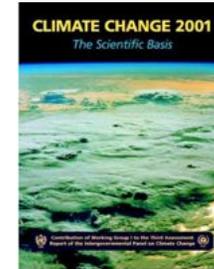
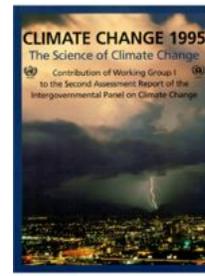
Negative Feedback  
Lower Sensitivity

# CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

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



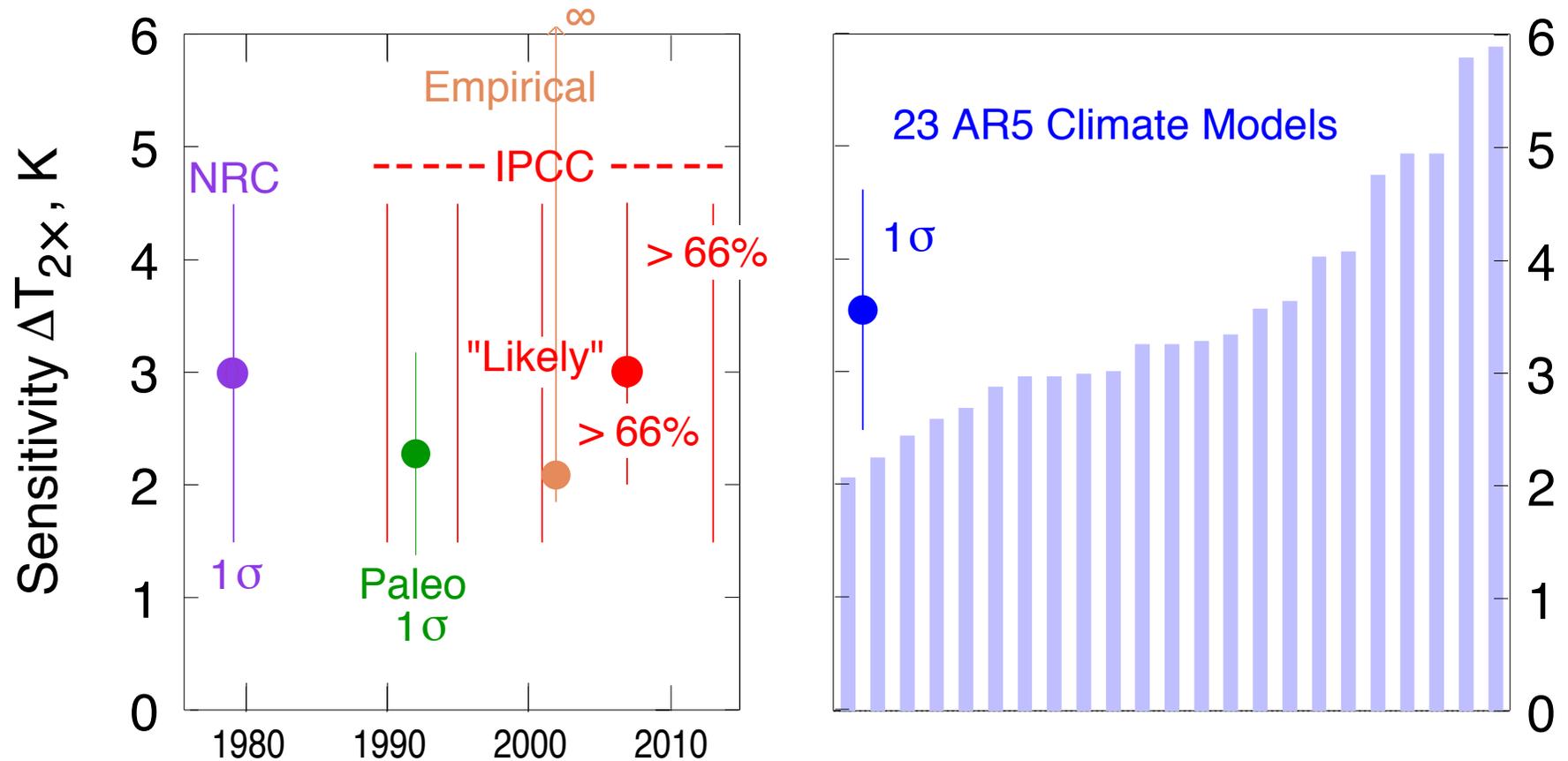
**Carbon Dioxide and Climate:  
A Scientific Assessment**  
NATIONAL ACADEMY OF SCIENCES  
Washington, D.C. 1979



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 CO<sub>2</sub> doubling temperature  $\Delta T_{2x} = 3.5$  K, but with substantial uncertainty.

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

## ?? QUESTION ??

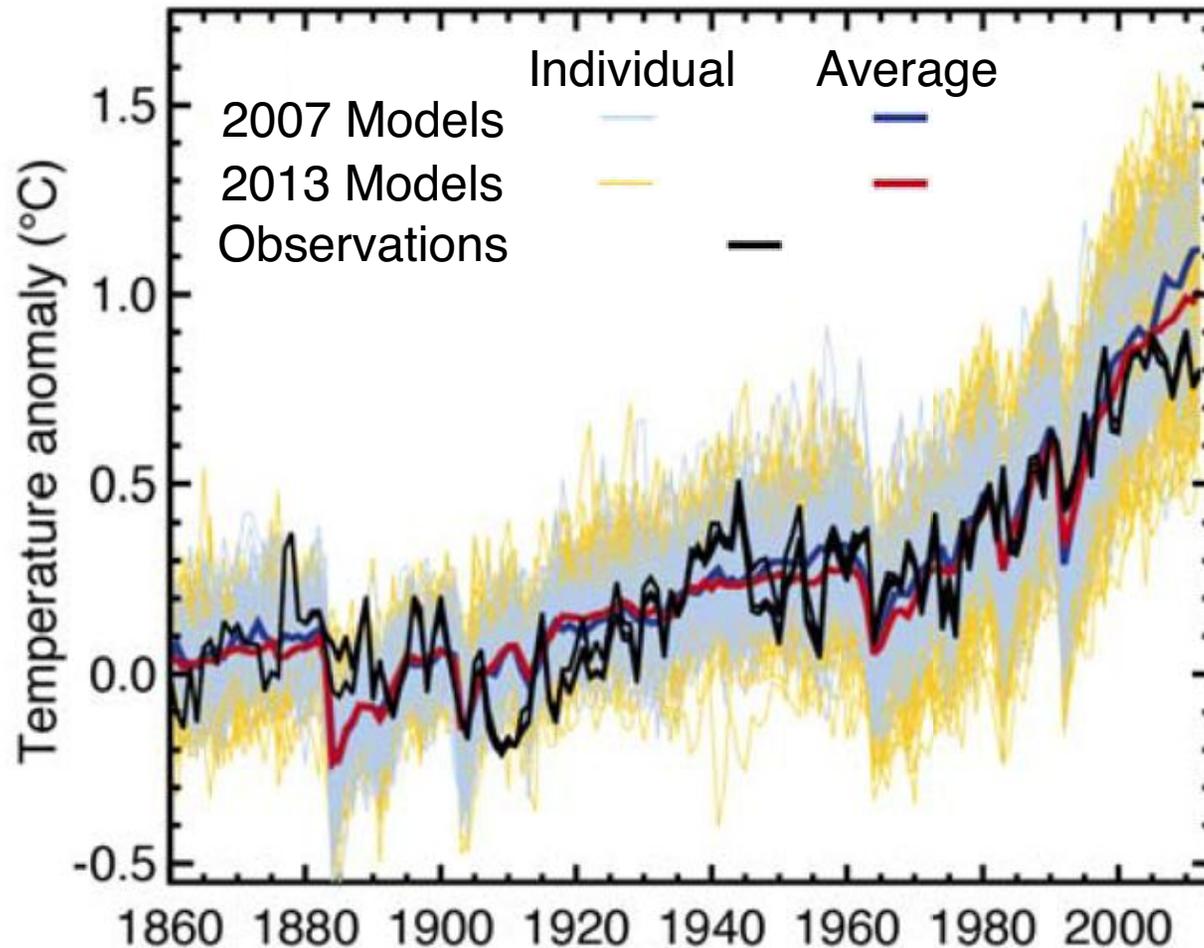
- Why is there such a large range of sensitivities in current climate models and why hasn't this situation improved much in thirty years?

## ANSWER

- This is a really tough scientific problem!

# 20<sup>th</sup> CENTURY TEMPERATURE ANOMALY

## Comparison of Measurements and Global Climate Models



*IPCC Fifth Assessment Report, 2013*

Despite very different sensitivities the models reproduce the observations.

***How can this be?***

# HOW MUCH WARMING IS EXPECTED?

For increases in long-lived greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and CFCs) over the industrial period

$$F = 2.8 \text{ W m}^{-2}$$

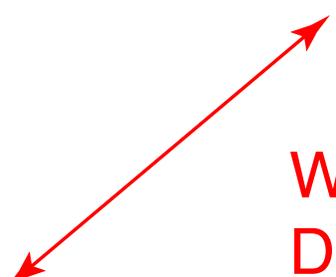
*Expected* temperature increase:

$$\Delta T_{\text{exp}} = \frac{F}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.8}{3.7} \times 3 \text{ K} = 2.3 \text{ K}$$

*Observed* temperature increase:

$$\Delta T_{\text{obs}} = 0.8 \text{ K}$$

Warming  
Discrepancy



*From Forcing by Long-lived Greenhouse Gases*  
**Why Hasn't Earth Warmed as Much as Expected?** 

STEPHEN E. SCHWARTZ

*Brookhaven National Laboratory, Upton, New York*

ROBERT J. CHARLSON

*University of Washington, Seattle, Washington*

RALPH A. KAHN

*NASA Goddard Space Flight Center, Greenbelt, Maryland*

JOHN A. OGREN

*NOAA/Earth System Research Laboratory, Boulder, Colorado*

HENNING RODHE

*Department of Meteorology, Stockholm University, Stockholm, Sweden*

# WHY HAS EARTH **NOT** WARMED AS MUCH AS EXPECTED... FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

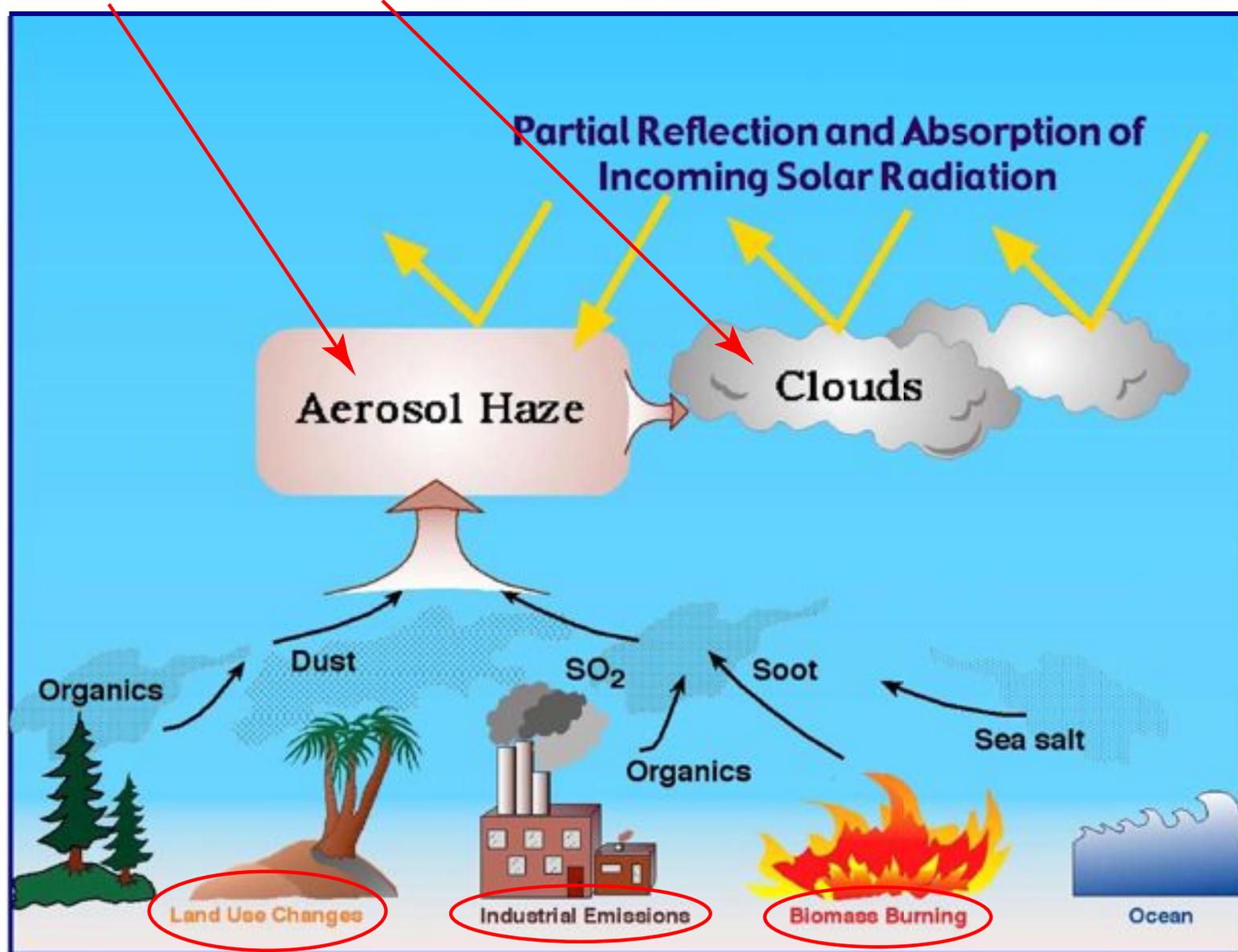
- ~~Uncertainty in greenhouse gas forcing.~~
- ~~Countervailing natural cooling over the industrial period.~~
- Lag in reaching thermal equilibrium. *about 20 % of the discrepancy*
- Countervailing cooling forcing by aerosols.
- Climate sensitivity lower than current estimates.

# Climate Forcing by Anthropogenic Aerosols

1992 R. J. CHARLSON, S. E. SCHWARTZ, J. M. HALES, R. D. CESS,  
J. A. COAKLEY, JR., J. E. HANSEN, D. J. HOFMANN

Science

DIRECT AND INDIRECT RADIATIVE INFLUENCES OF AEROSOLS



# AEROSOL IN MEXICO CITY BASIN



Atmospheric Science Program (ASP)

*Photo: Berk Knighton*

# AEROSOL IN MEXICO CITY BASIN

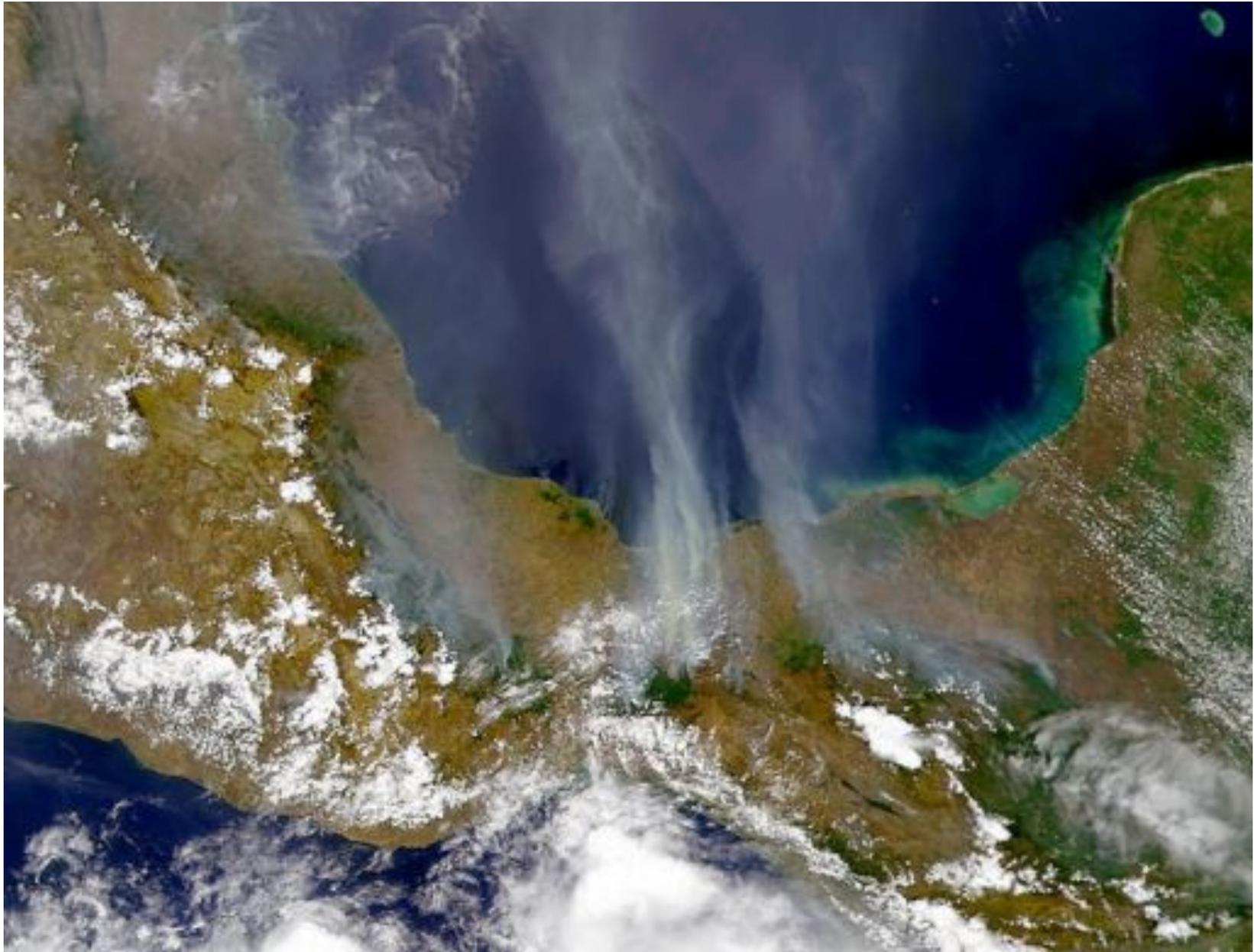


Atmospheric Science Program (ASP)

*Photo: Berk Knighton*

Light scattering by aerosols decreases absorption of solar radiation.

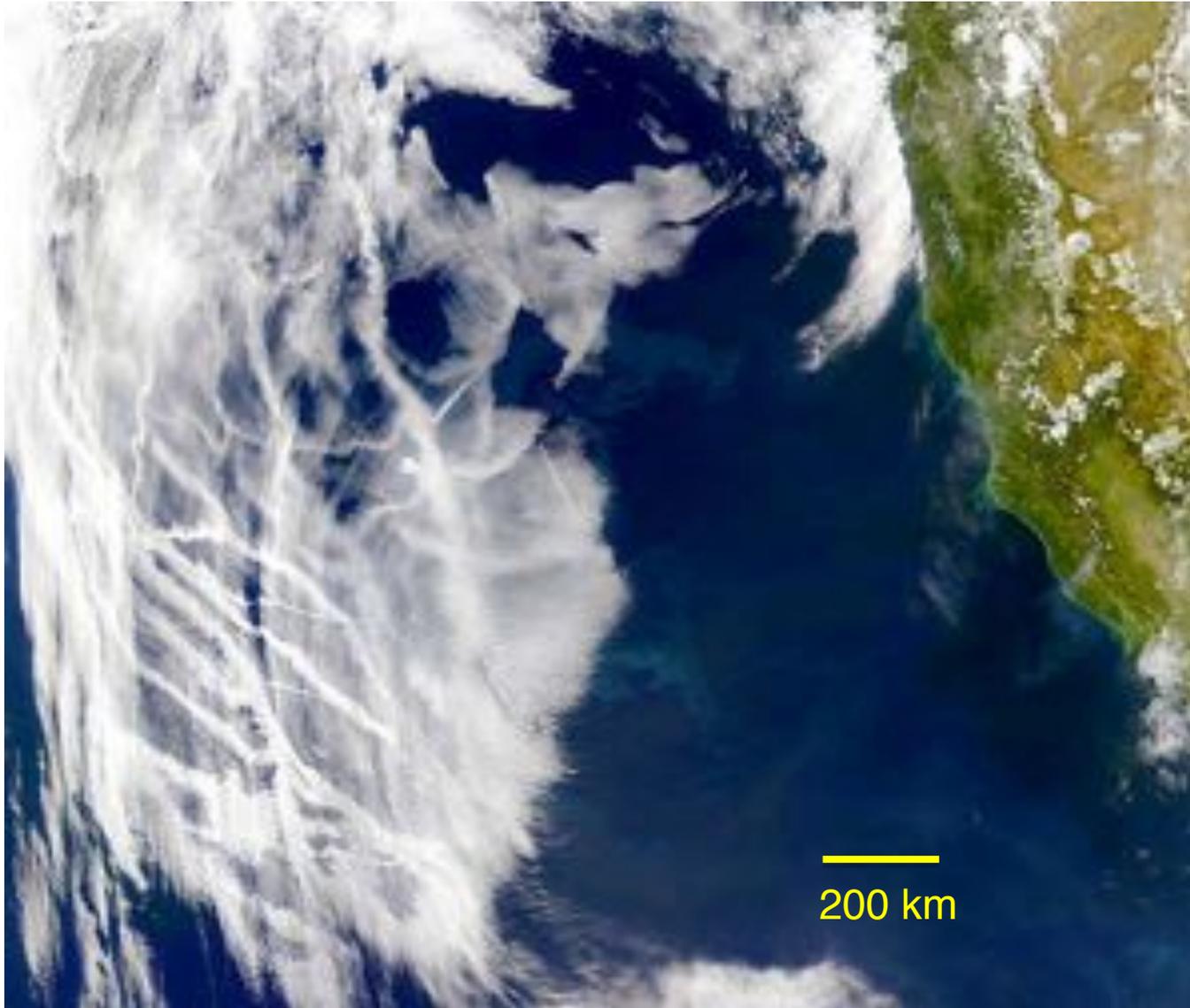
# AEROSOLS AS SEEN FROM SPACE



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

# CLOUD BRIGHTENING BY SHIP TRACKS

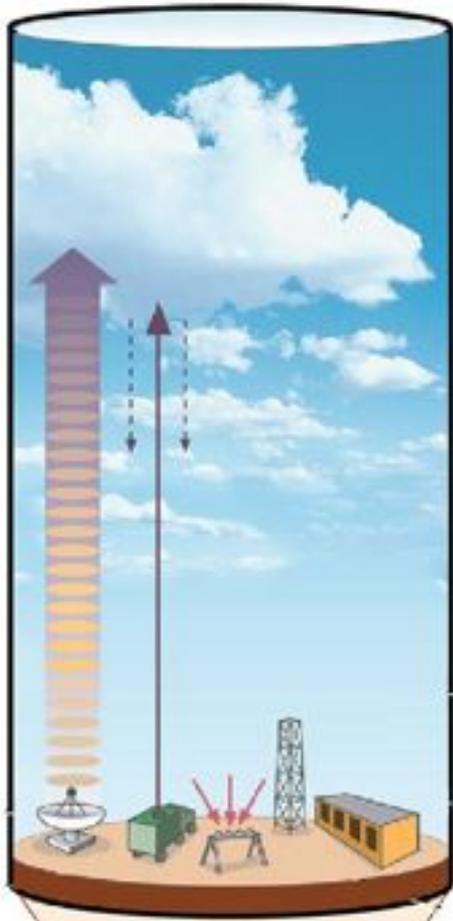
Satellite photo off California coast



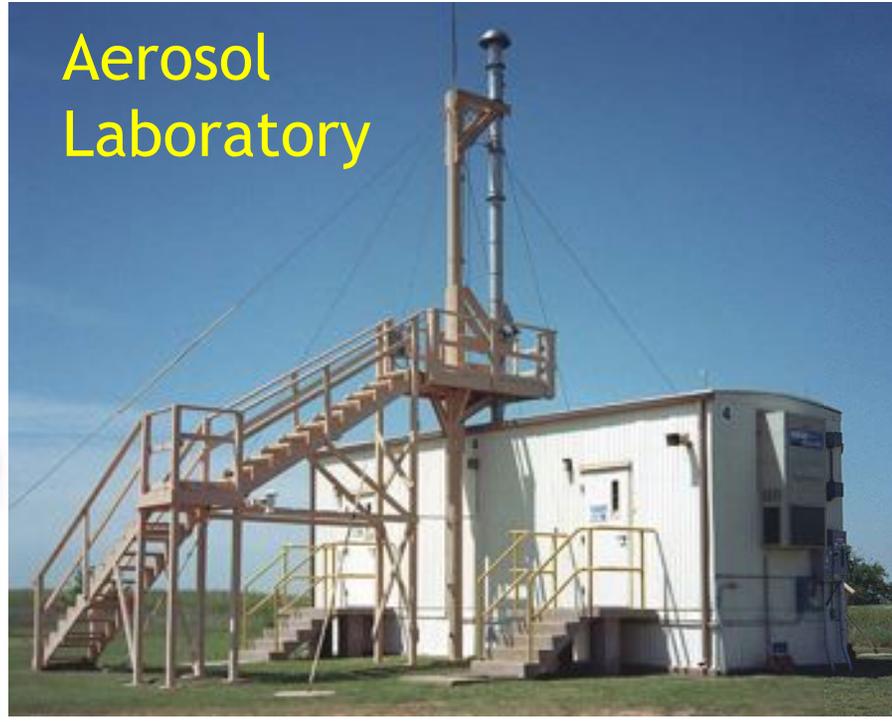
*Credit: SeaWiFS*

Aerosols from ship emissions enhance reflectivity of marine stratus.

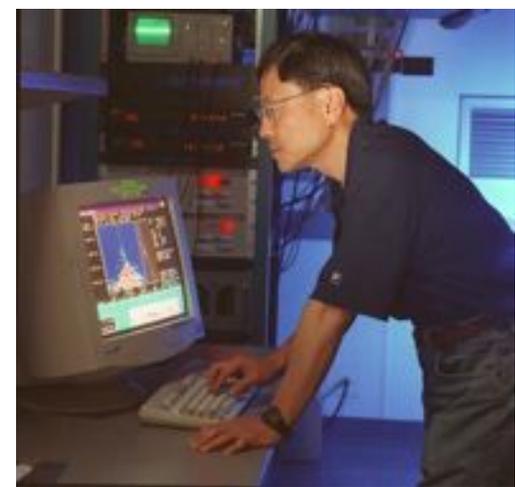
# DOE Atmospheric Radiation Measurement Climate Research Facility



Radiometers

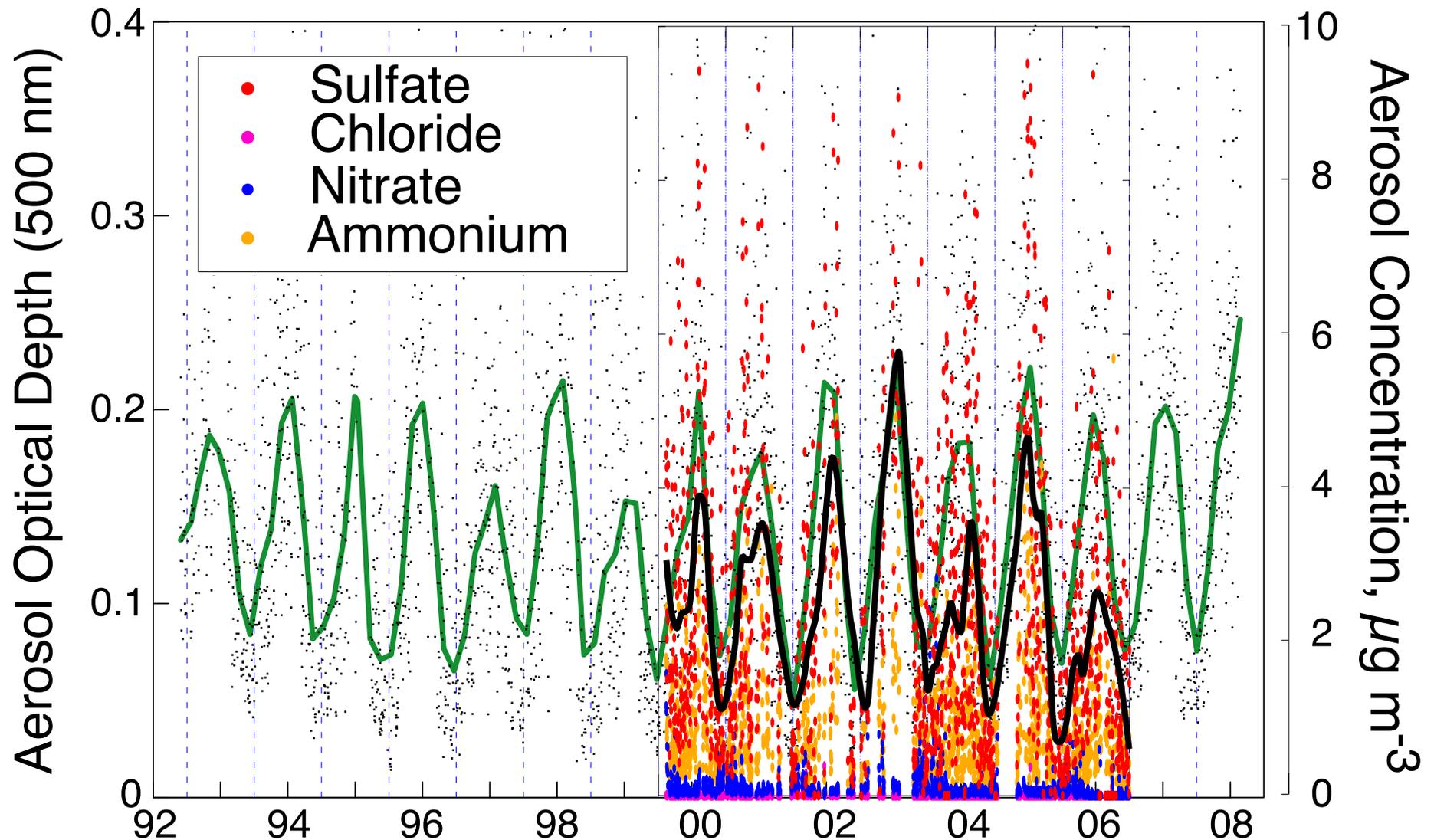


Aerosol Laboratory



# AEROSOL OPTICAL DEPTH AT ARM SGP

Fifteen years of daily average AOD in North Central Oklahoma



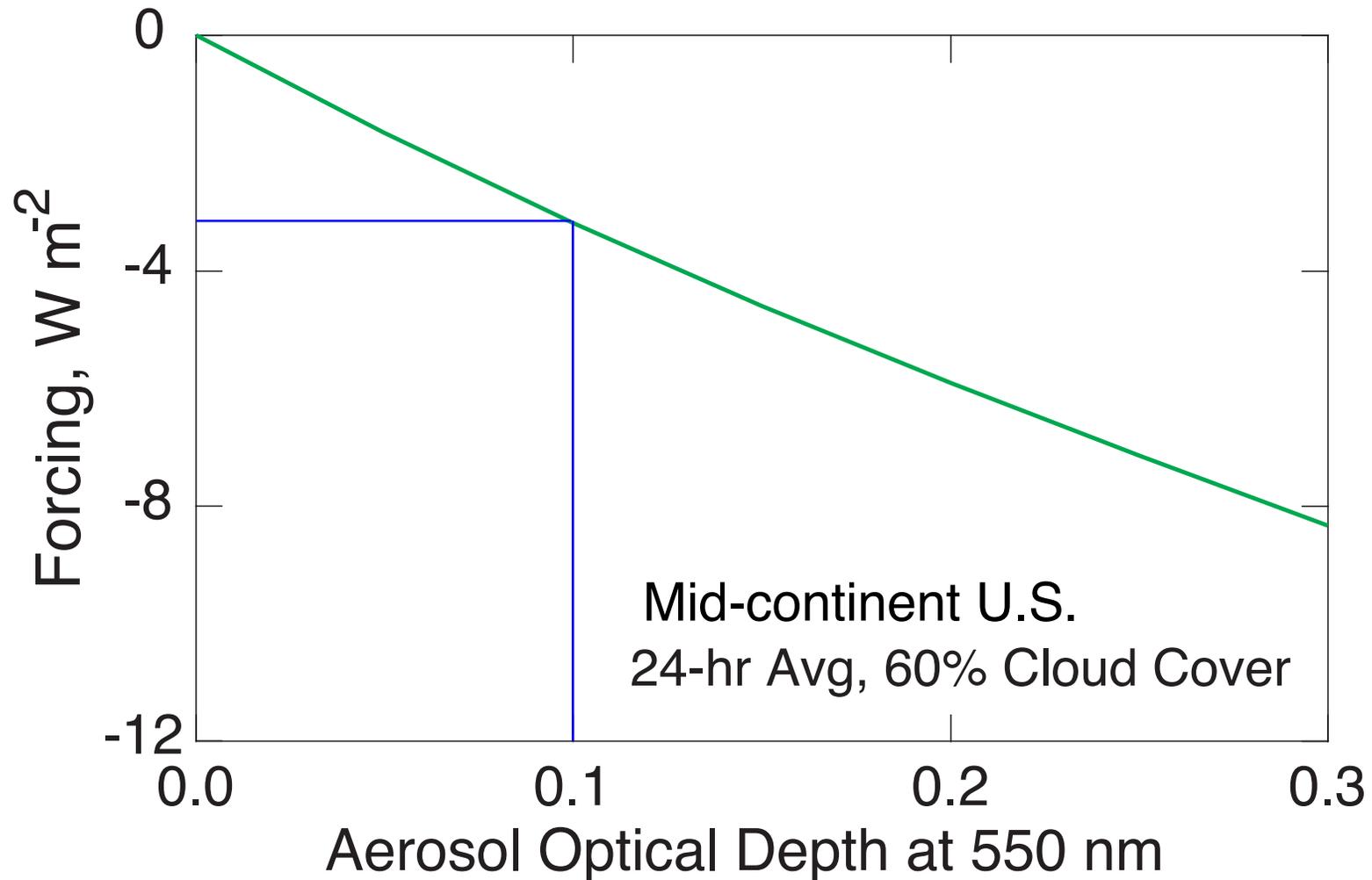
*Michalsky, Denn, Flynn, Hodges, Kiedron, Koontz, Schlemmer, Schwartz, JGR, 2010*

*Chemical data: P. Quinn, NOAA*

Green curve, locally weighted smooth fit, shows summertime maximum.  
Black curve, locally weighted smooth fit to sulfate concentration.

# ESTIMATES OF AEROSOL DIRECT FORCING

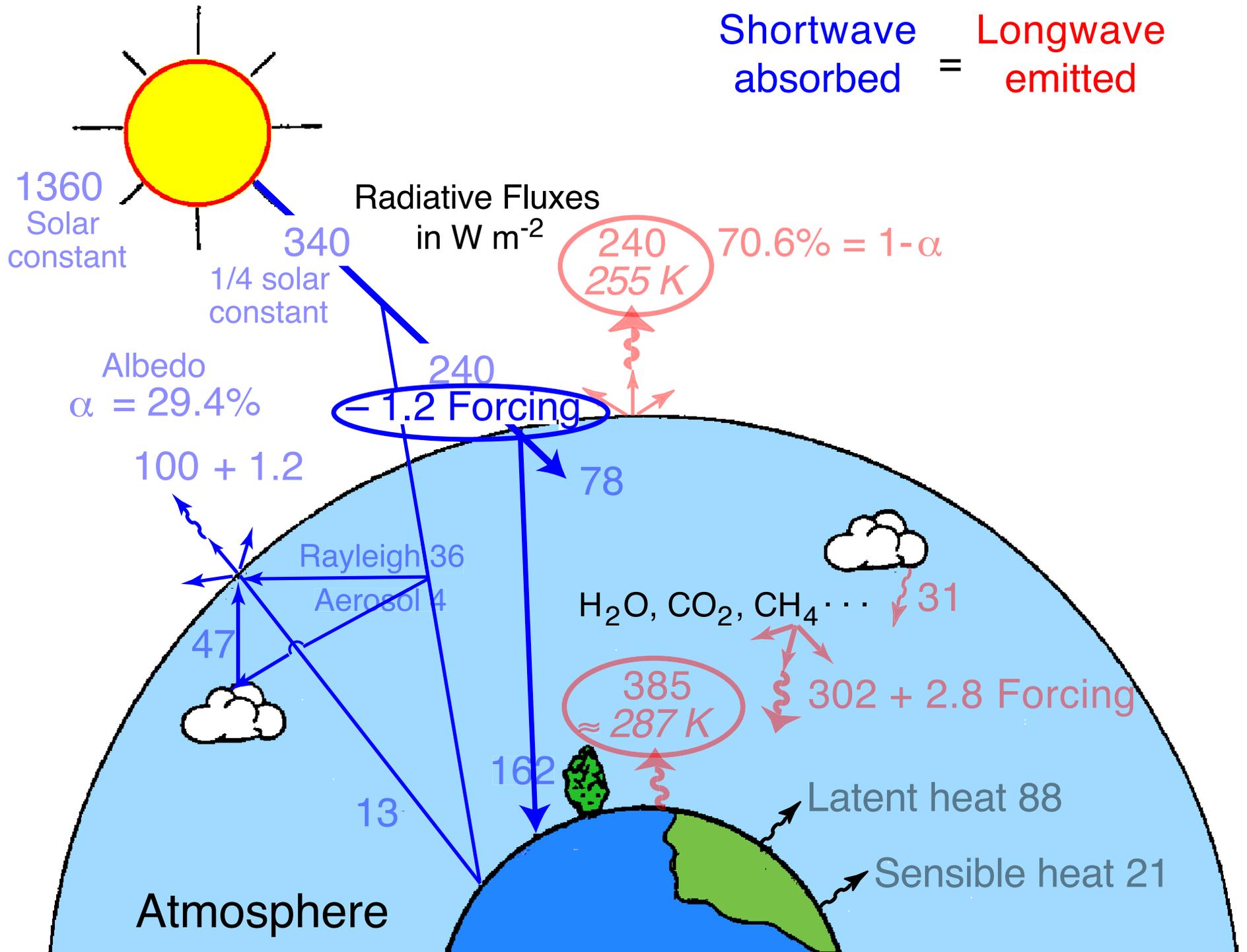
By radiation transfer modeling



*Continental U. S.* typical aerosol optical depth is 0.1:  **$3 W m^{-2}$  cooling forcing.**

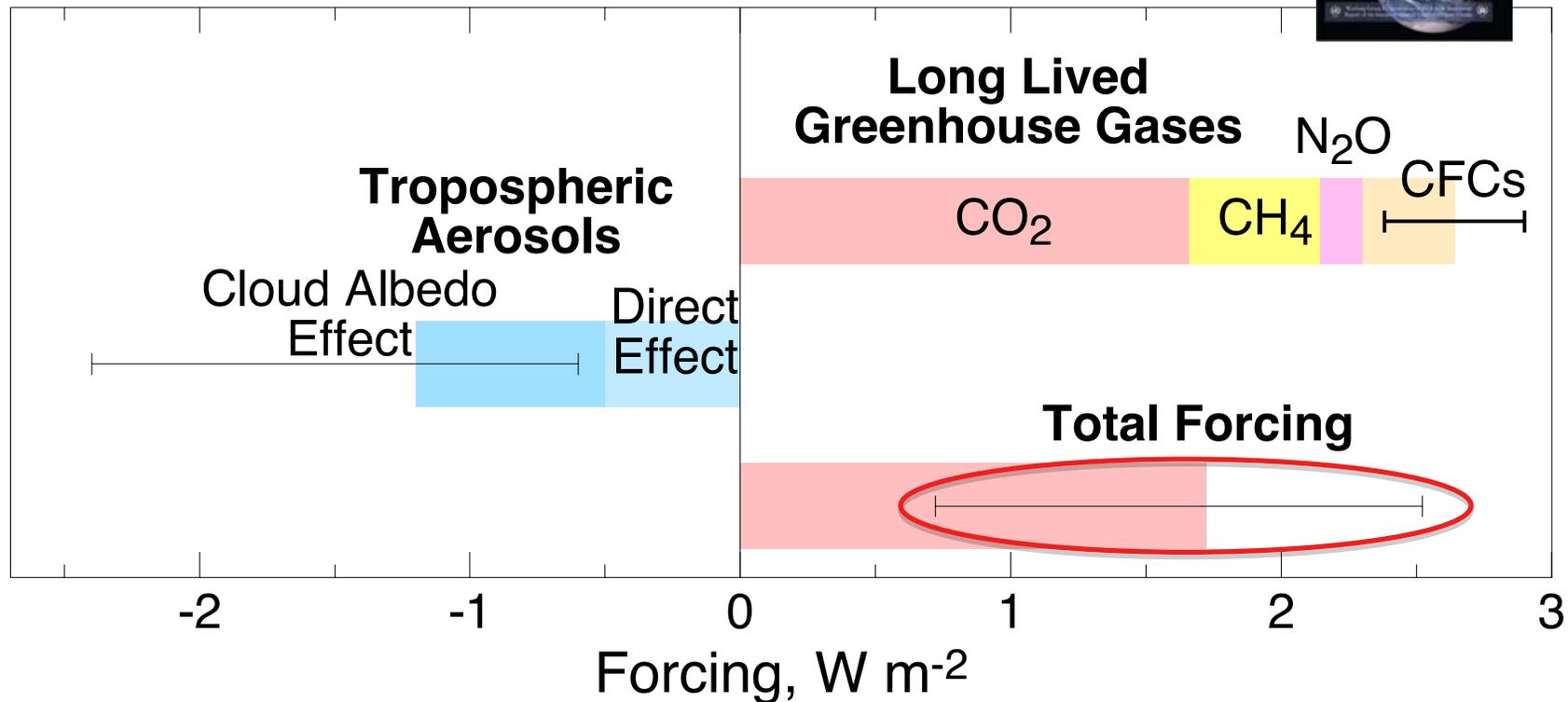
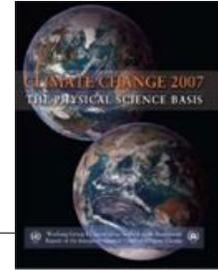
# EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT

Shortwave absorbed = Longwave emitted



# CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)



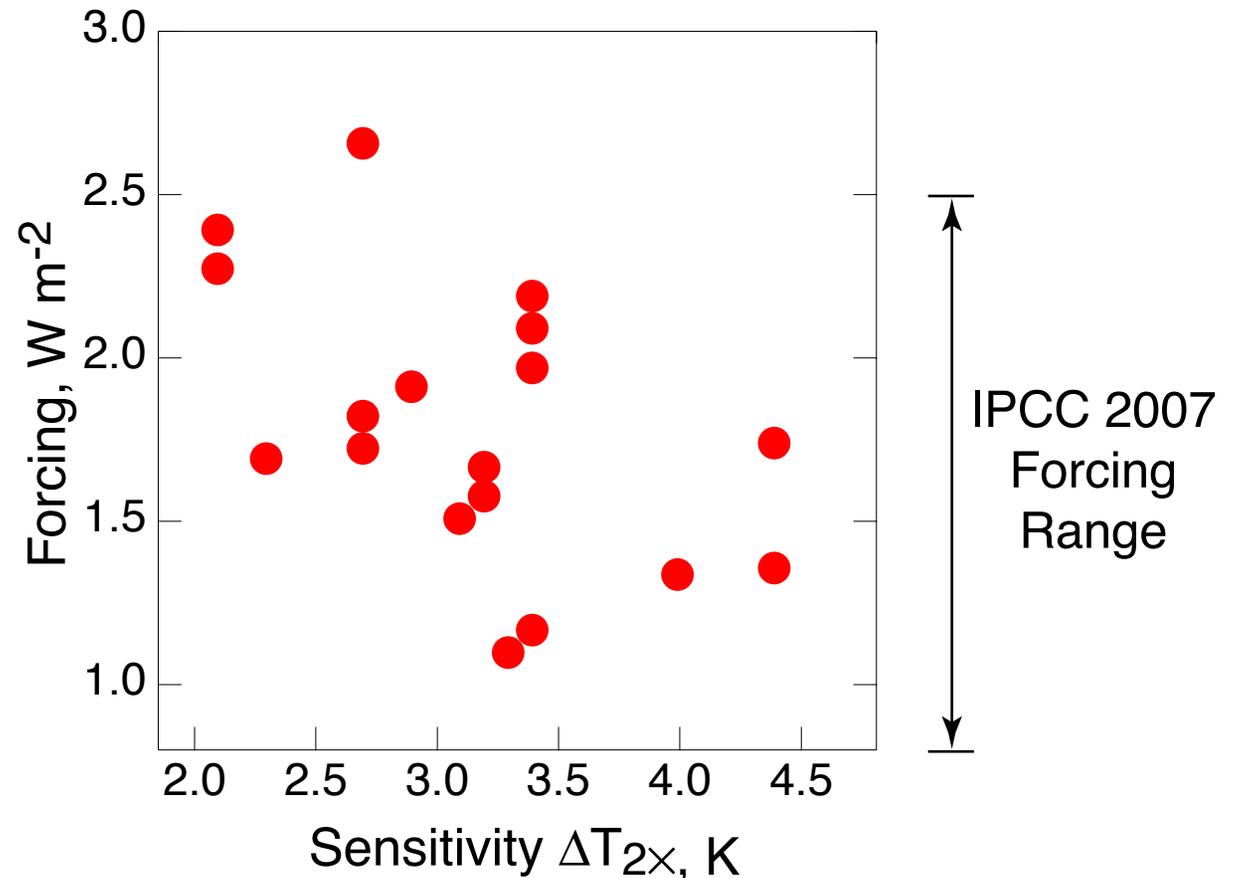
Aerosol forcing may offset much of the greenhouse gas forcing.

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

# CORRELATION OF FORCING AND SENSITIVITY IN CLIMATE MODELS

18 IPCC 2007 climate models

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



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

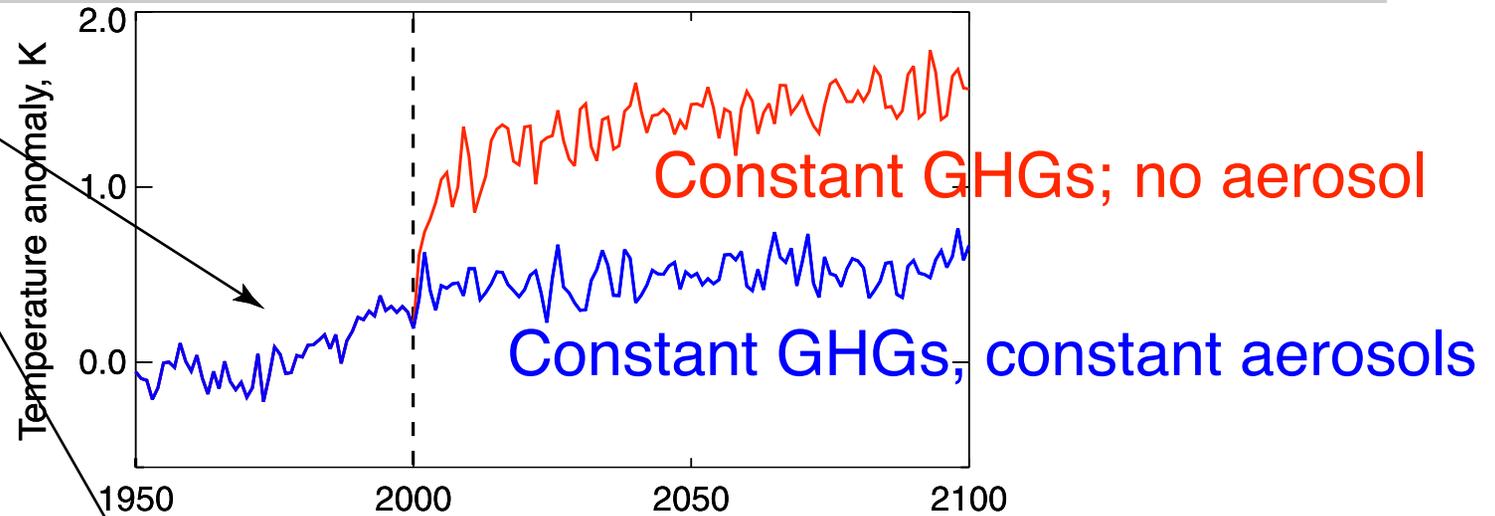
To reproduce observed 20<sup>th</sup> century temperature increase, models with low sensitivity employed large forcing, and vice versa.

# USING CLIMATE MODELS TO ANSWER “WHAT IF” QUESTIONS

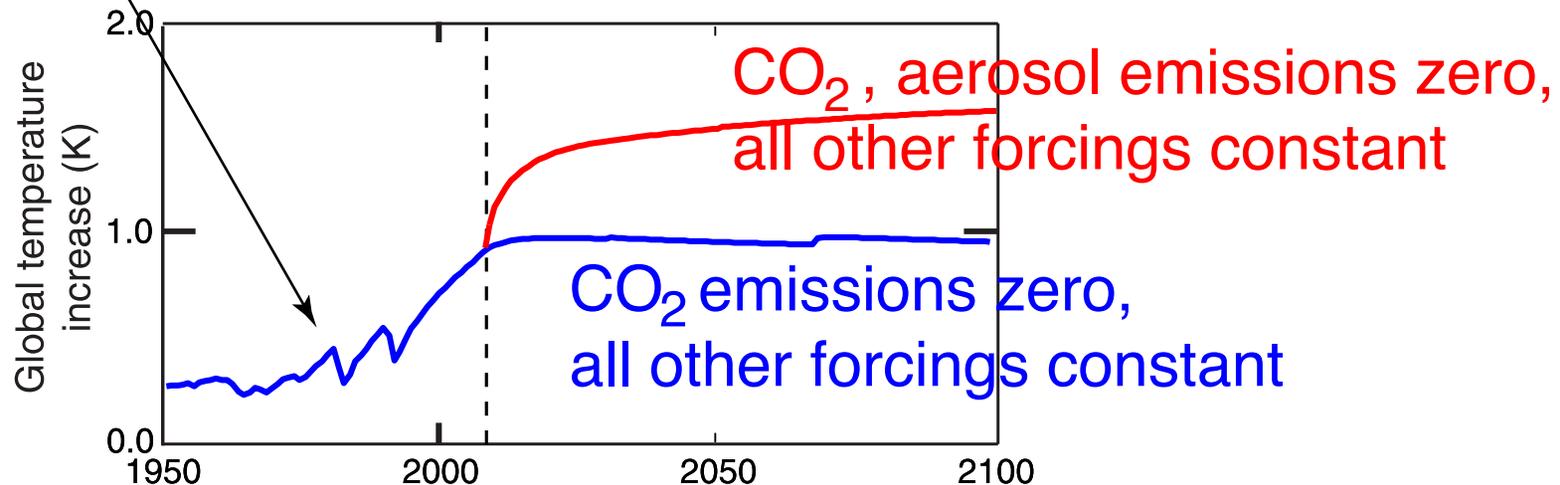
Turn off CO<sub>2</sub> emissions *and aerosol forcing*

Increasing GHGs  
and aerosols

Hamburg ECHAM-5  
coupled ocean-  
atmosphere model  
*Brasseur & Roeckner  
GRL, 2007*



Bern 2D  
intermediate  
complexity carbon  
cycle-climate model  
*Knutti & Plattner  
J Climate, 2012*



Global temperature *rapidly increases* when aerosol forcing is halted.

## ?? QUESTION ??

- Why is all this so important?

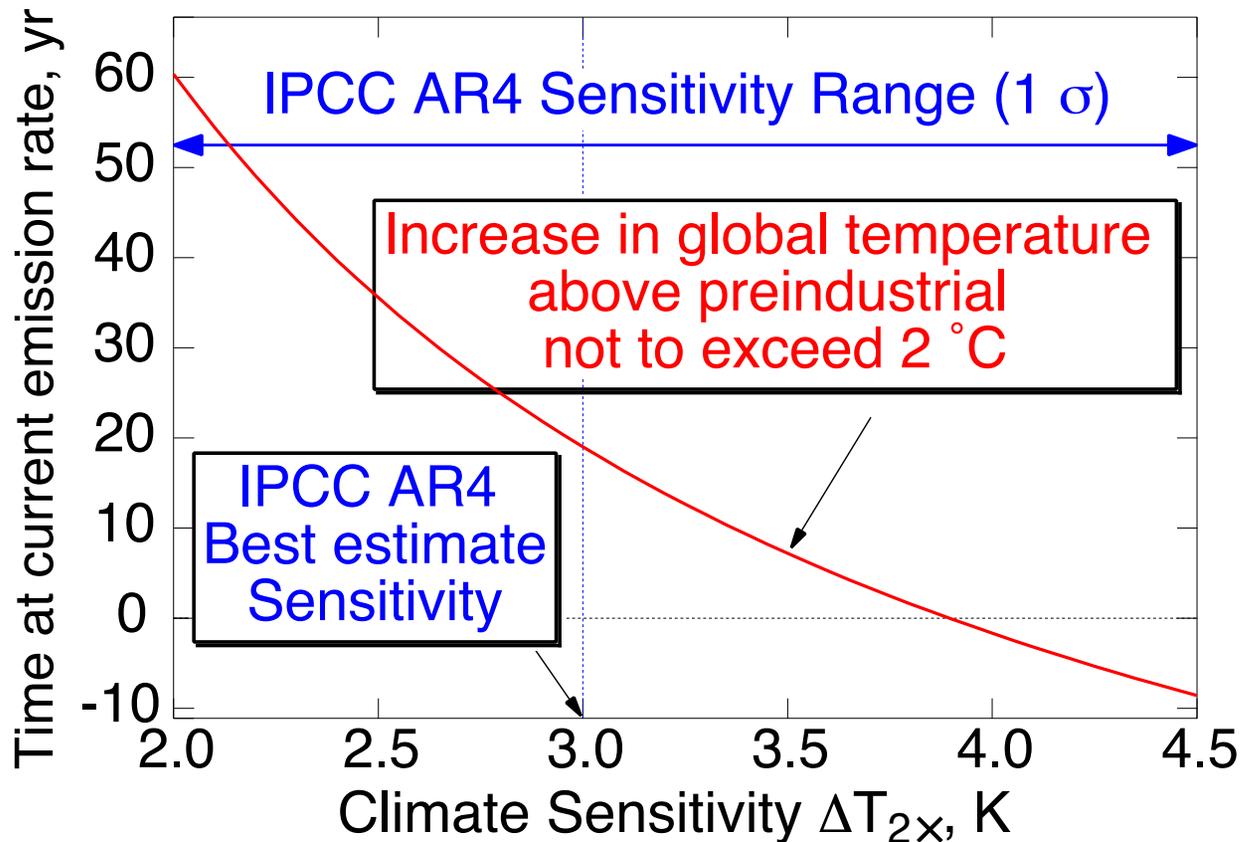
## KEY QUESTION

- How much more CO<sub>2</sub> can be emitted without committing Earth to a temperature increase of 2 °C above preindustrial?

# ALLOWABLE FUTURE GLOBAL CO<sub>2</sub> EMISSION

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

Based on greenhouse gas forcing only, current forcing 2.8 W m<sup>-2</sup>

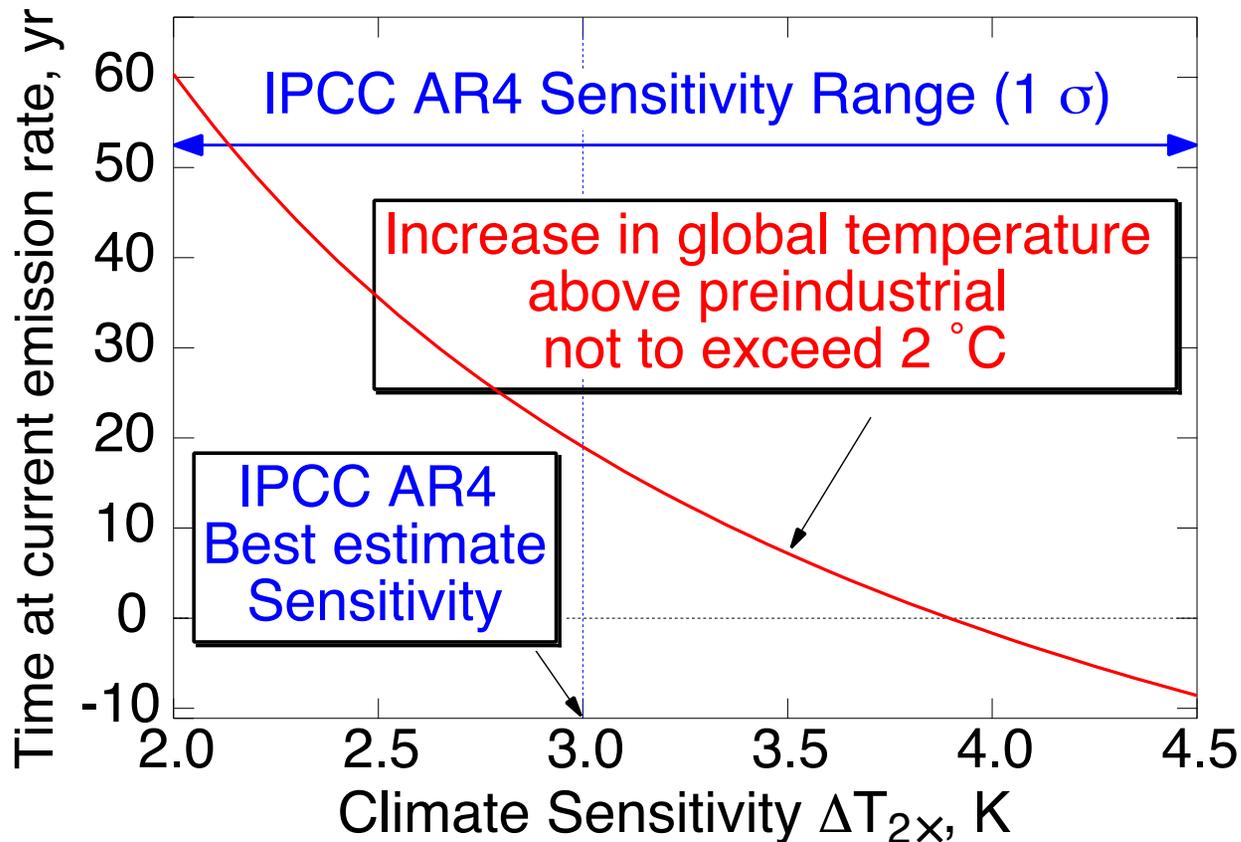


For IPCC best-estimate sensitivity, *only about 20 years* more emission at current rate.

# ALLOWABLE FUTURE GLOBAL CO<sub>2</sub> EMISSION

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

Based on greenhouse gas forcing only, current forcing 2.8 W m<sup>-2</sup>



For IPCC best-estimate sensitivity, *only about 20 years* more emission at current rate.

For IPCC sensitivity range, allowable future emission at current rate ranges from *+60 years to -10 years*.

# SUMMARY AND CONCLUSIONS I

- The “greenhouse effect” is an essential feature of Earth’s climate system.
- The *enhanced* greenhouse effect is about 1% of Earth’s radiation budget.
- Observed increase in global temperature is  $\sim 0.5$  K ( $\sim 0.5$  %).
- Best estimate expected warming due to increases in long-lived greenhouse gases alone is about 2.3 K, or 1.9 K after accounting for non-steady state response. This is a *half an ice age*.
- The *warming discrepancy* is 1.2 K, more than a factor of 2.

# SUMMARY AND CONCLUSIONS II

- The warming discrepancy is due to some mix of aerosol forcing and/or lower climate sensitivity.
- Aerosol atmospheric residence times are short. If emissions are halted (or reduced) aerosol forcing will rapidly decrease and global temperature would be expected to increase over a decade. The aerosol offset is a *Faustian bargain*.
- Allowable future CO<sub>2</sub> emissions such that the planet is not committed to 2 K increase over preindustrial is *uncertain even in sign*.

*This is a very difficult scientific problem.*

