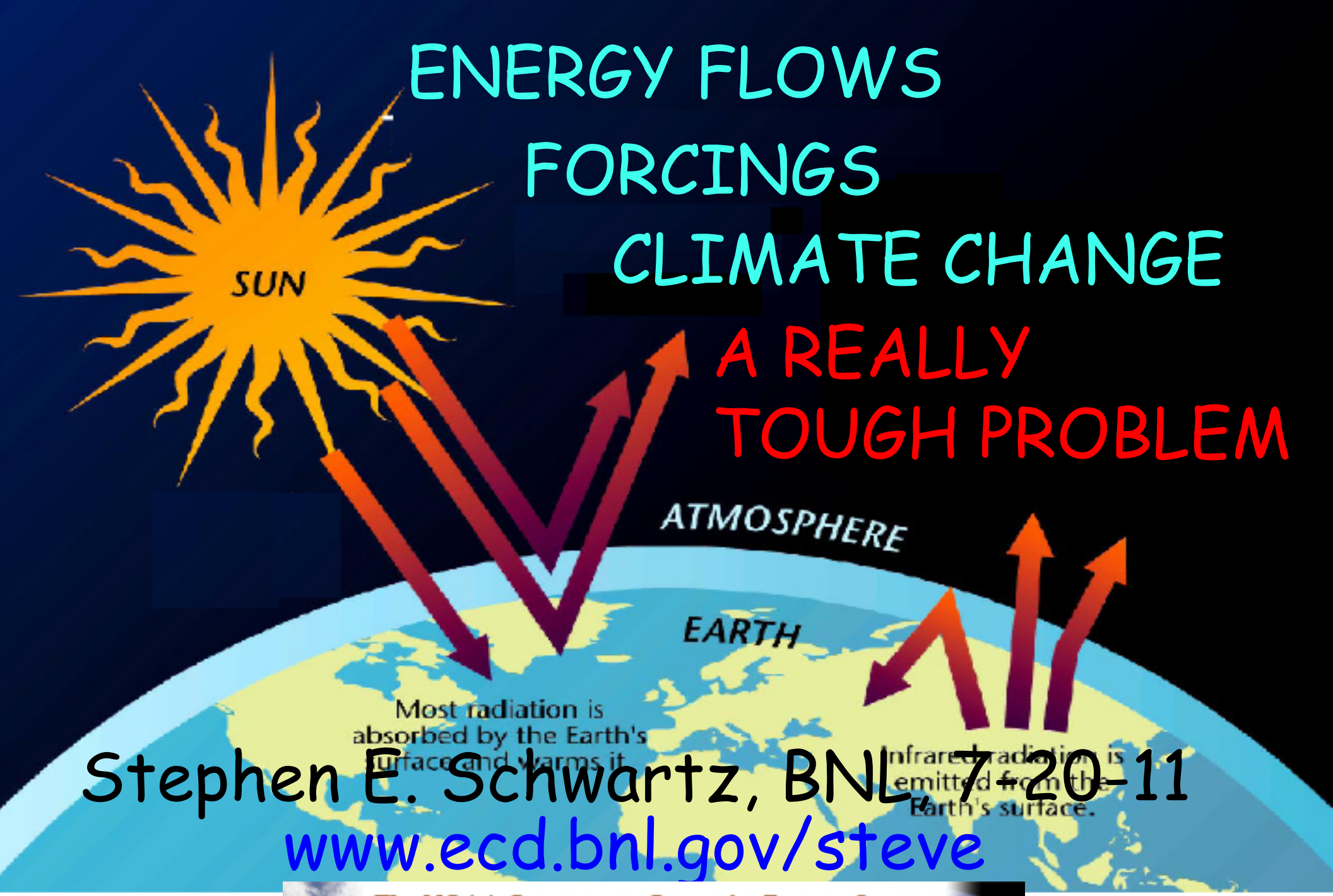
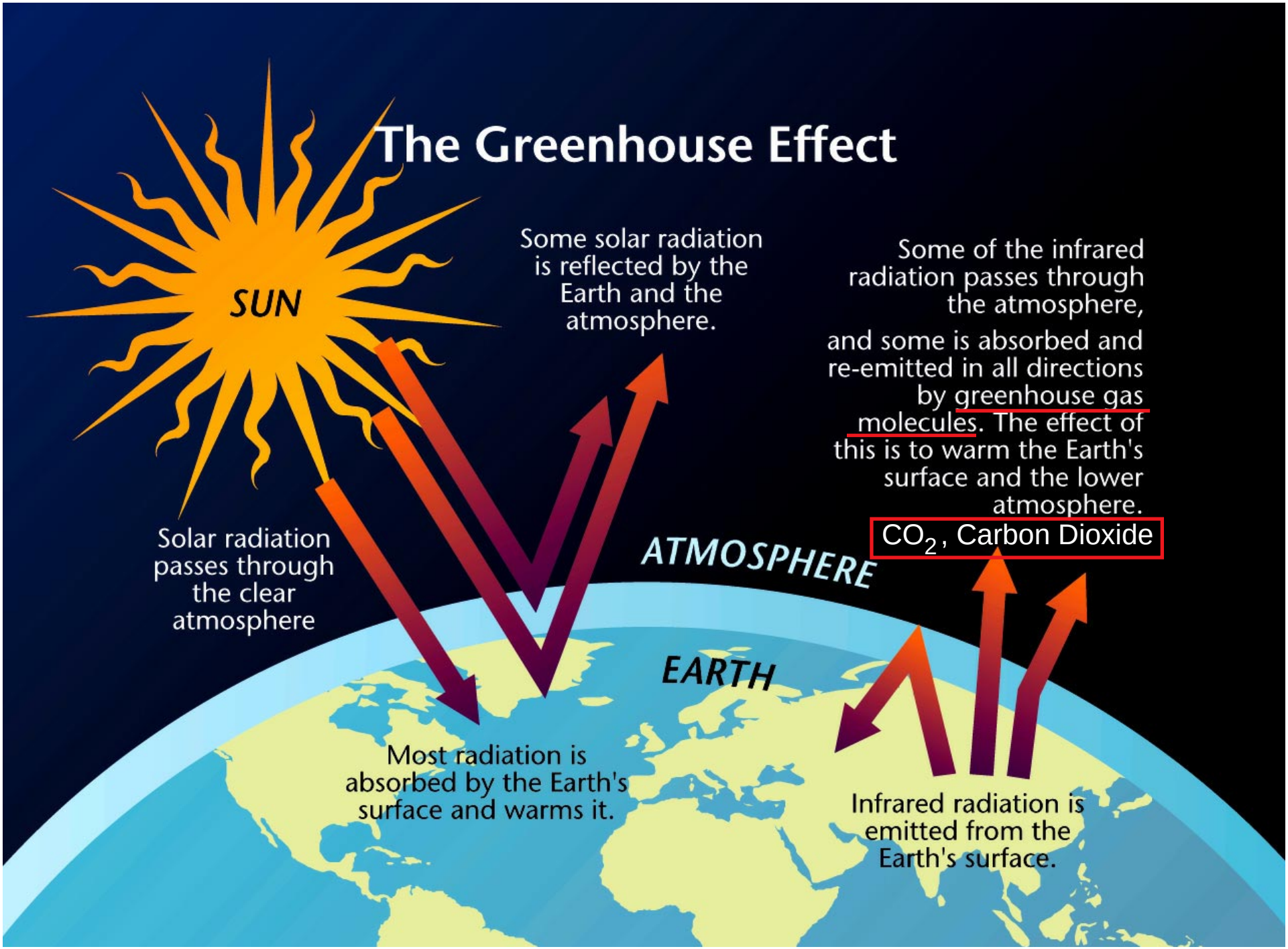
ENERGY FLOWS
FORCINGS
CLIMATE CHANGE

A REALLY TOUGH PROBLEM

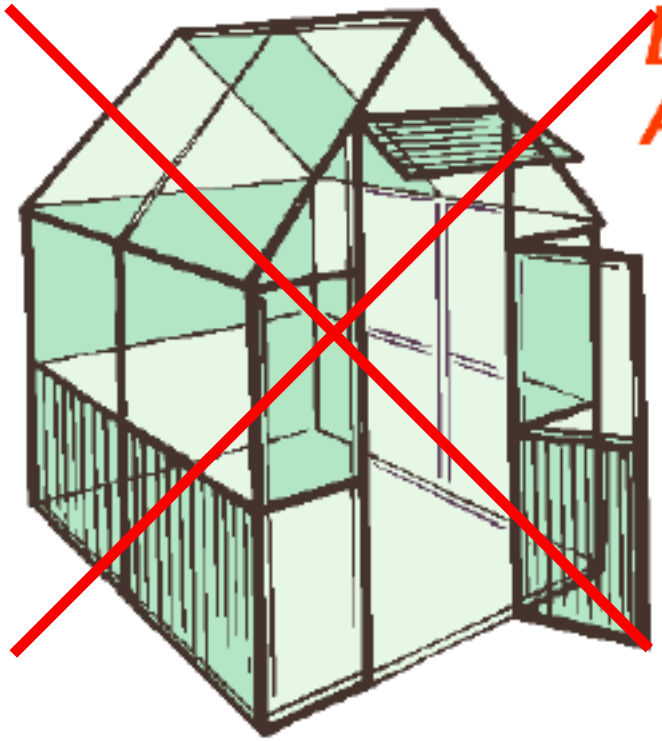


Stephen E. Schwartz, BNL, 7-20-11
www.ecd.bnl.gov/steve

The NOAA Cooperative Center for Remote Sensing Science and Technology at the City College of the City University of New York (CREST)


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.
CO_2, Carbon Dioxide
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.

THE GREENHOUSE EFFECT



EARTH'S ENERGY BUDGET: A DELICATE BALANCE

- Sunlight heats the Earth.
- The warm Earth radiates energy (in the form of infrared radiation, or heat) back out to space.
- Some of this infrared radiation is trapped in the atmosphere, giving Earth its temperate climate.

This is the greenhouse effect.

Global average temperature 15°C or 59°F

Without it, the Earth's climate would be like the moon's, harsh and severe.

Global average temperature -19°C or -2 °F

ATMOSPHERIC RADIATION

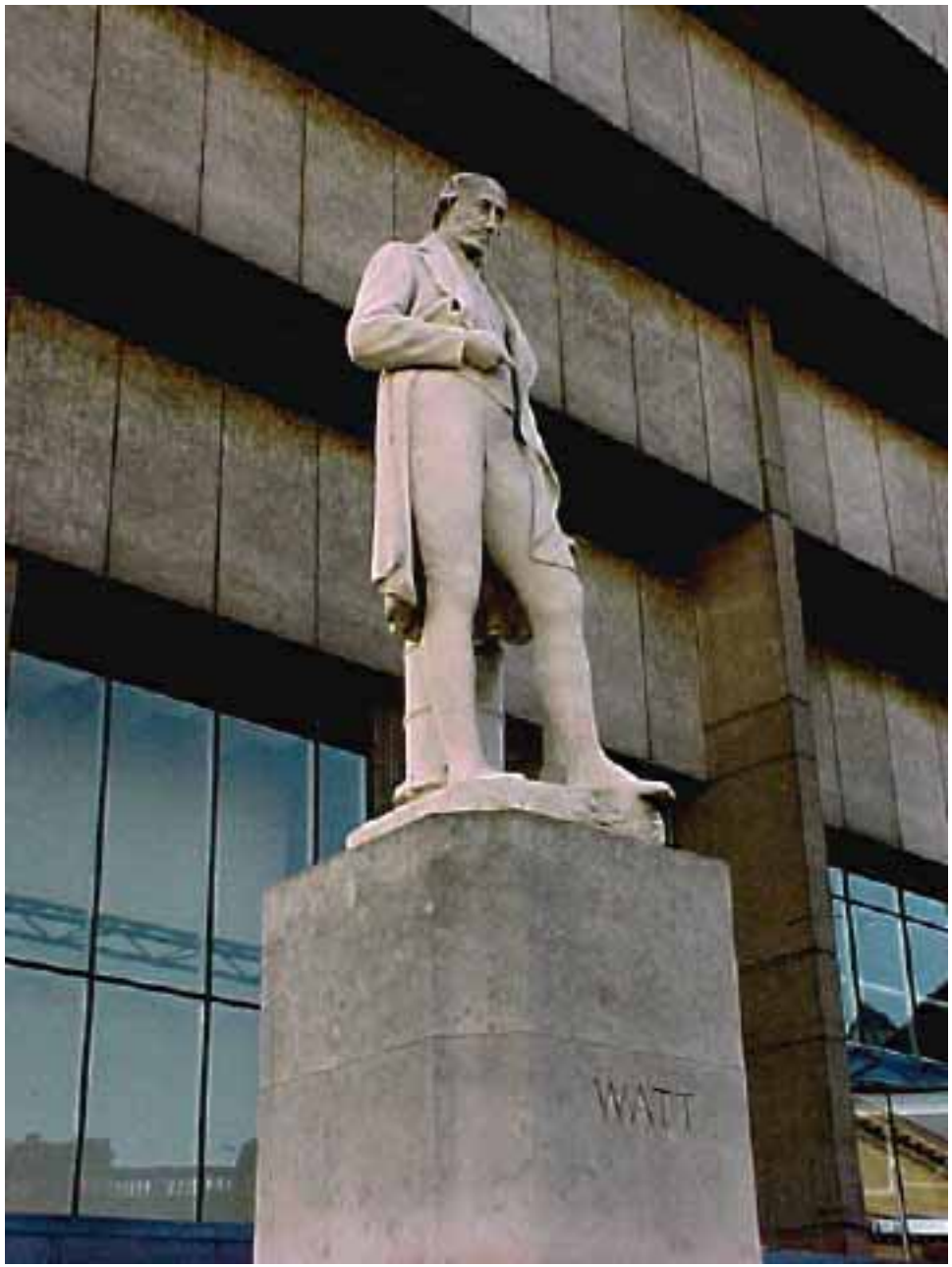
Power per area

Energy per time per area

Unit:

Watt per square meter

$W\ m^{-2}$



STEFAN - BOLTZMANN RADIATION LAW

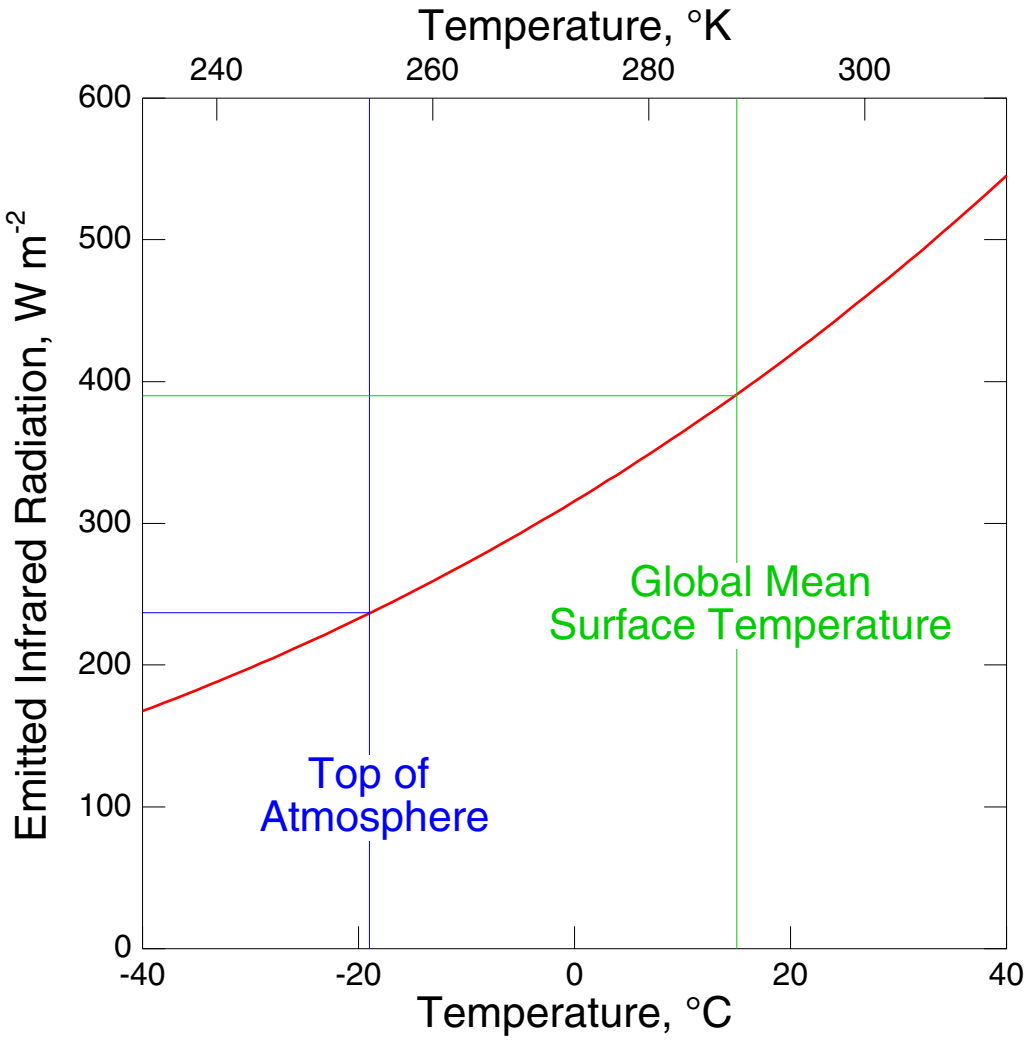
Emitted thermal radiative flux from a black body

$$F = \sigma T^4$$

F = Emitted flux, W m^{-2}

T = Absolute temperature, K

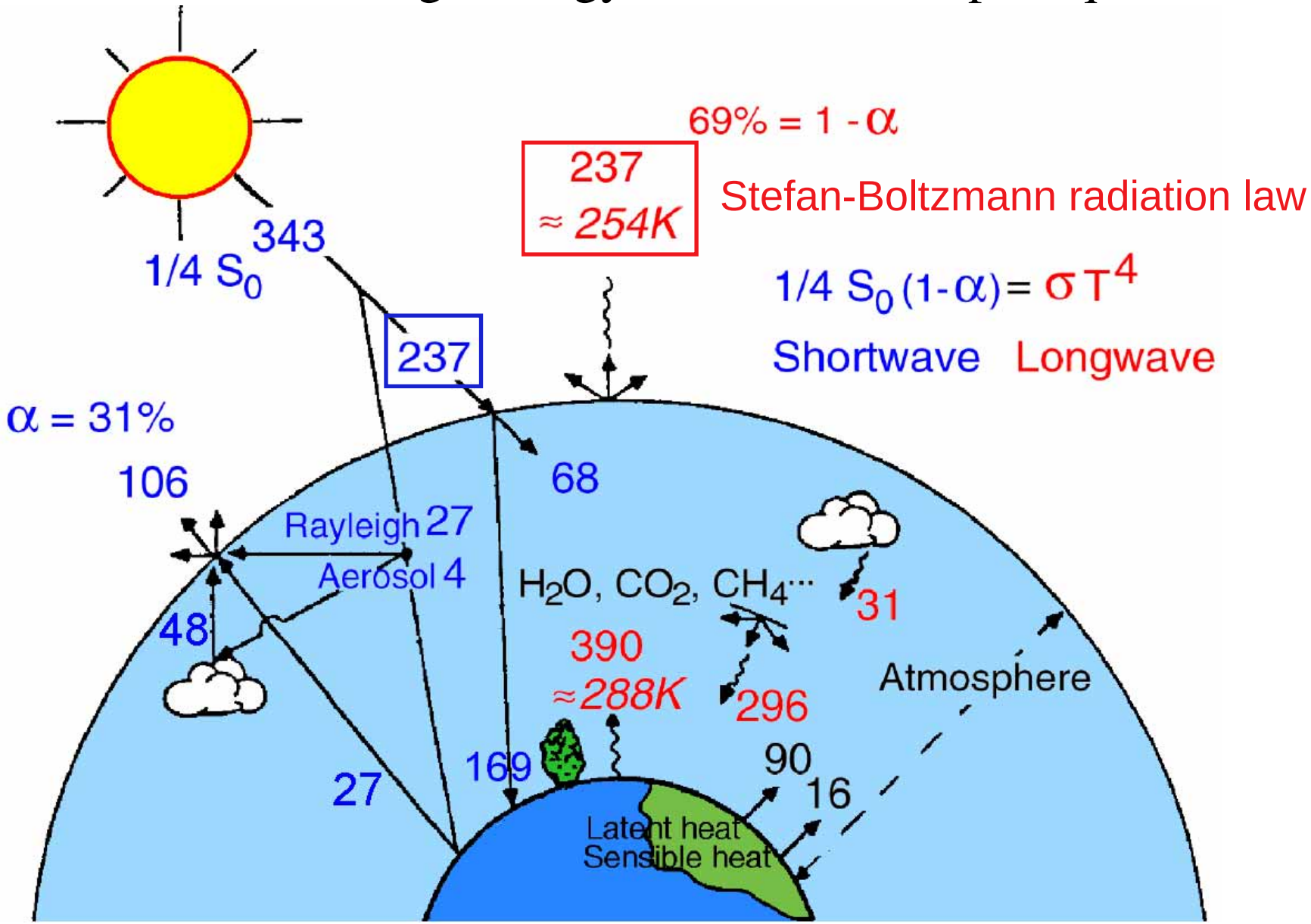
σ = Stefan-Boltzmann constant, W m^{-2} K^{-4}



Stefan-Boltzmann law "converts" temperature to radiative flux.

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

RADIATIVE FORCING

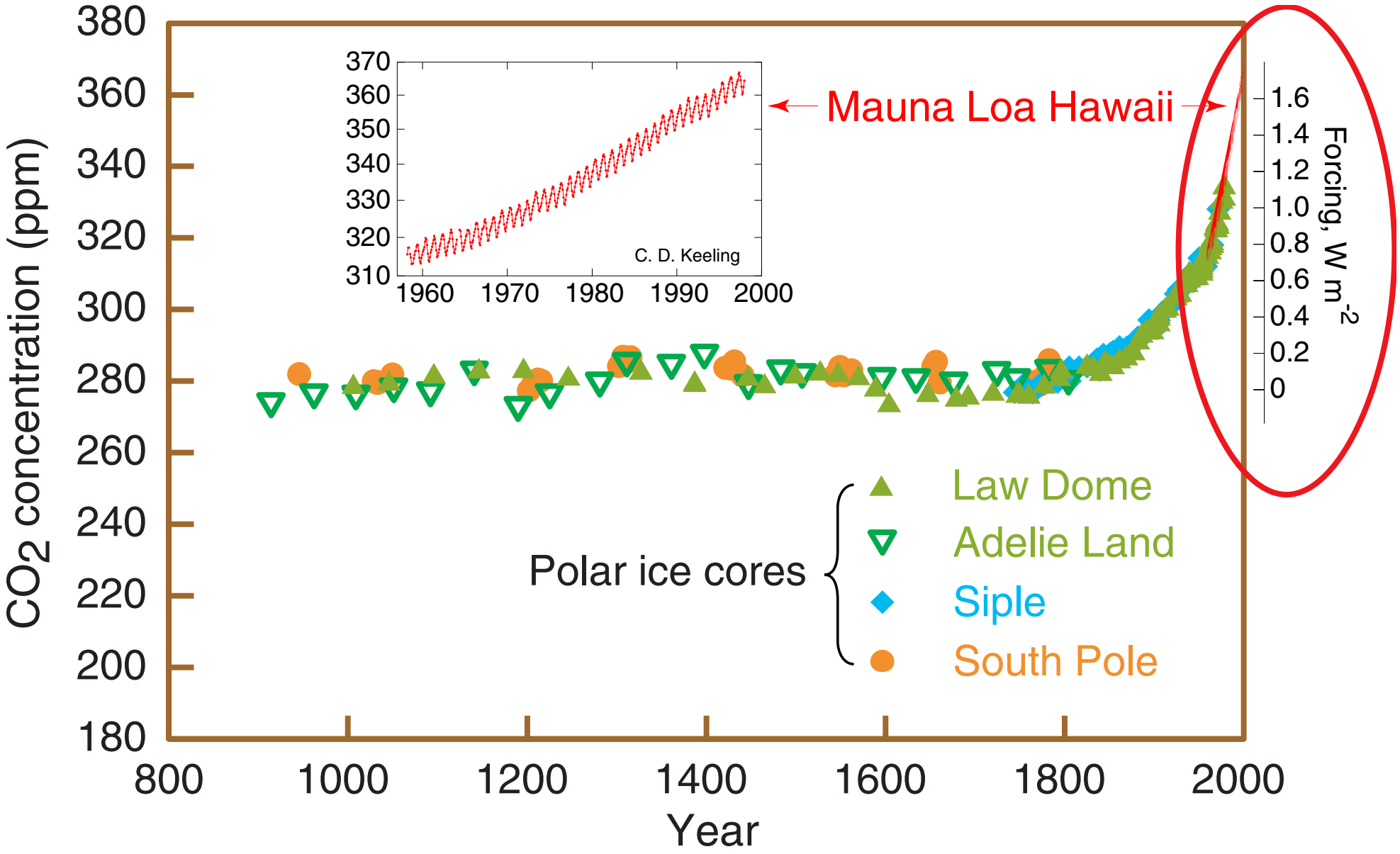
A ***change*** in a radiative flux term in Earth's radiation budget, ΔF, W m^{-2}.

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.

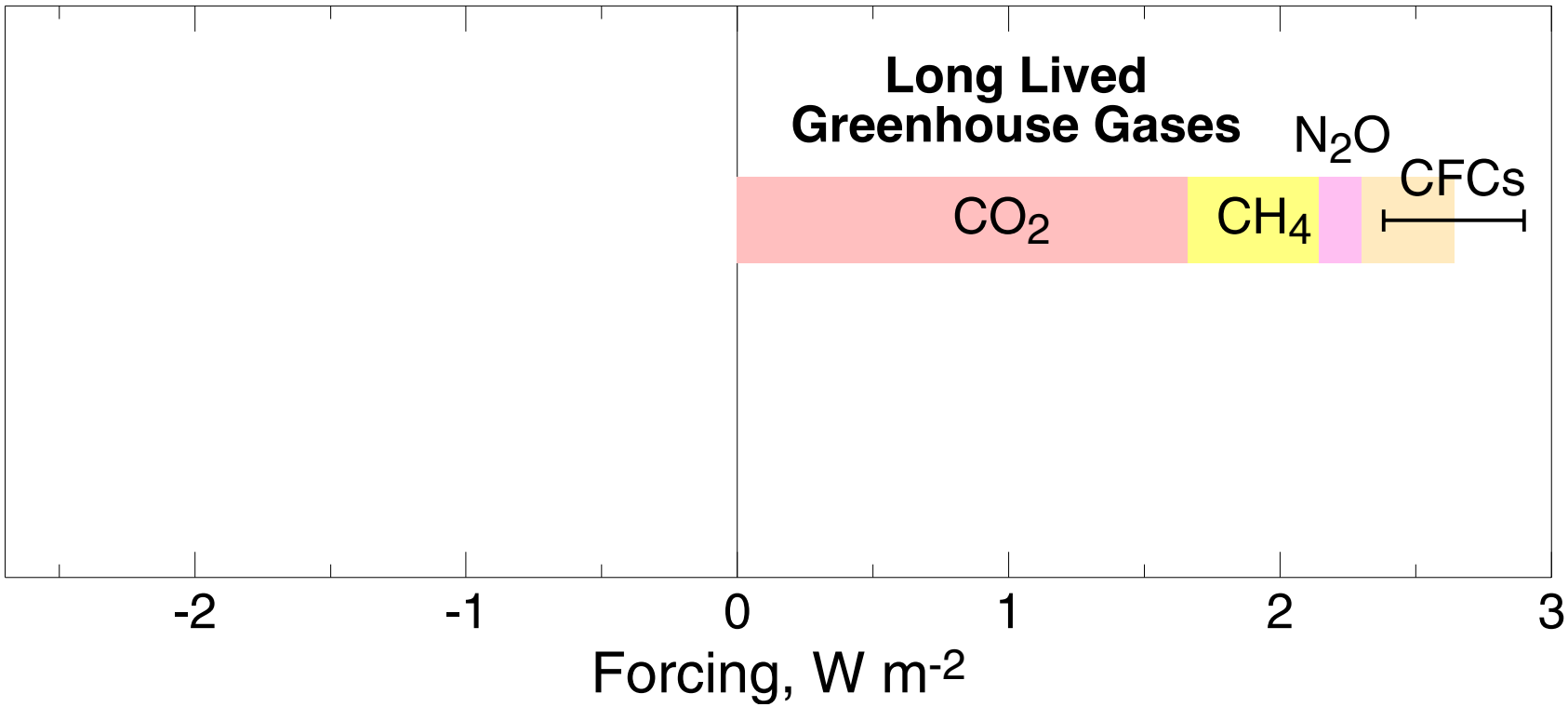
ATMOSPHERIC CARBON DIOXIDE IS INCREASING



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

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)

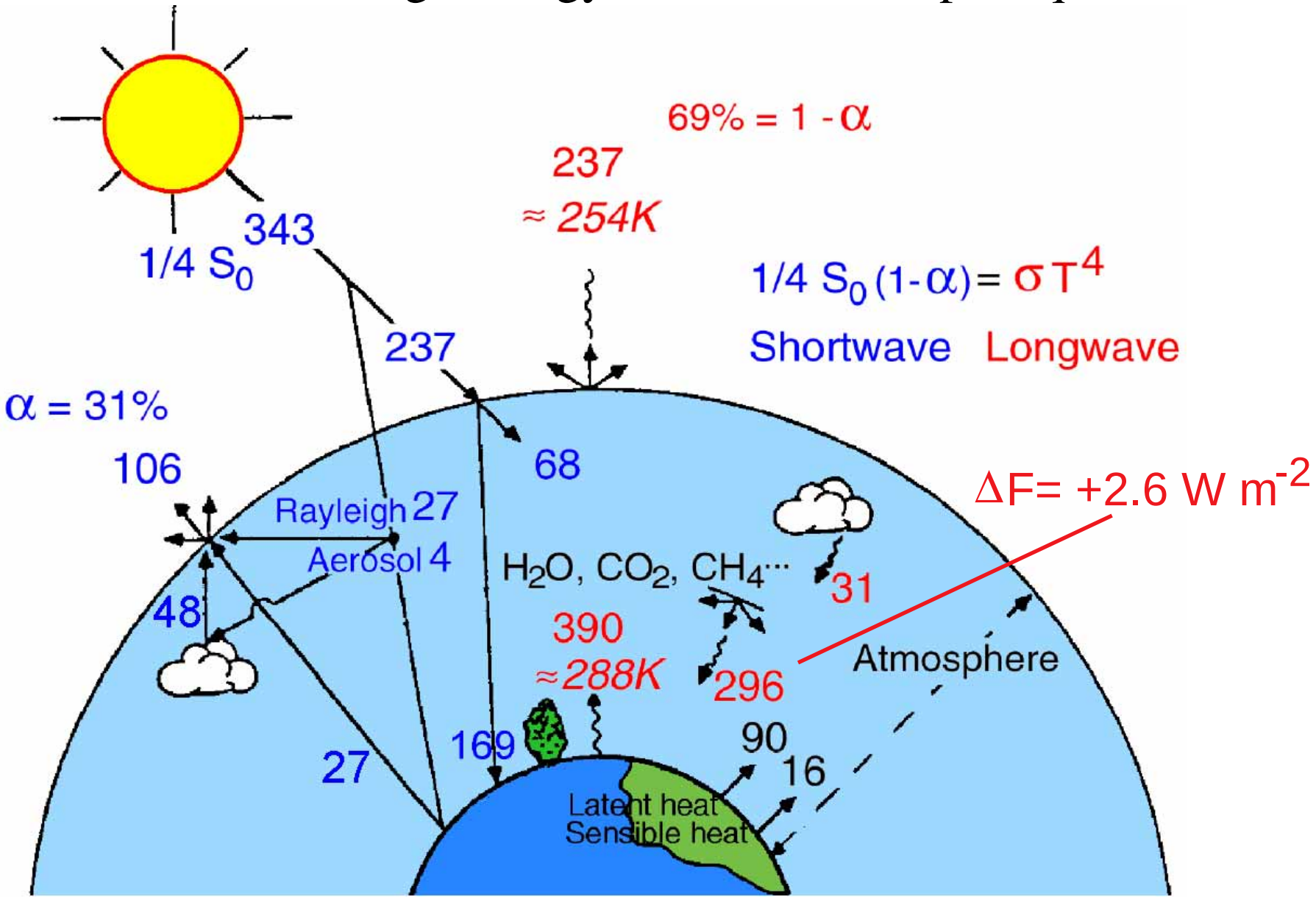


Greenhouse gas forcing is considered accurately known.

Gases are uniformly distributed; radiation transfer is well understood.

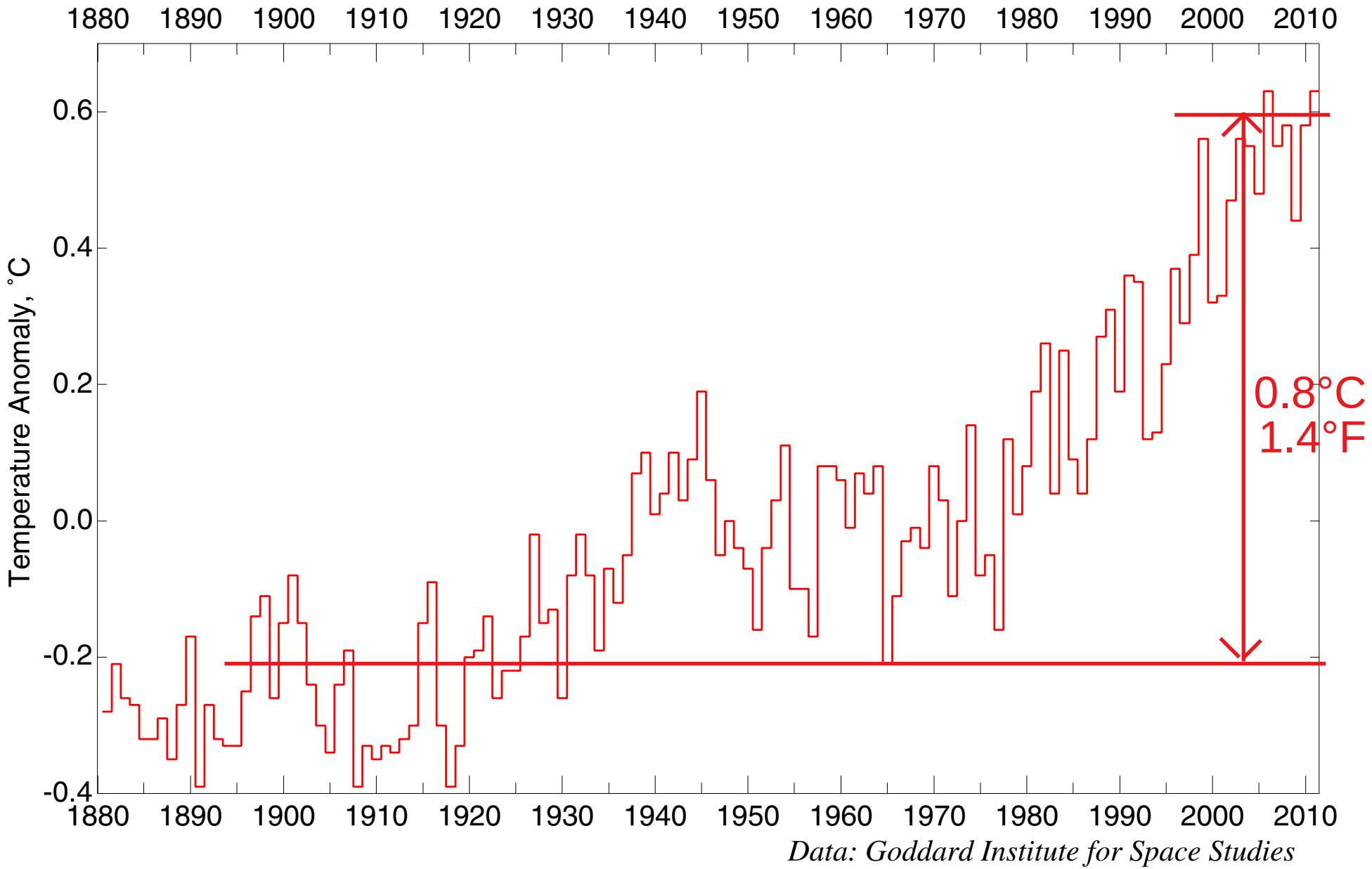
GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

GLOBAL ANNUAL TEMPERATURE ANOMALY, 1880-2010



Data: Goddard Institute for Space Studies

HOW MUCH WARMING IS EXPECTED?

$$\begin{array}{c}\text{Equilibrium change}\\ \text{in global mean}\\ \text{surface temperature}\end{array} = \begin{array}{c}\text{Climate}\\ \text{sensitivity}\end{array} \times \text{Forcing}$$

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

S is ***equilibrium*** sensitivity. Units: K/(W m^{-2})

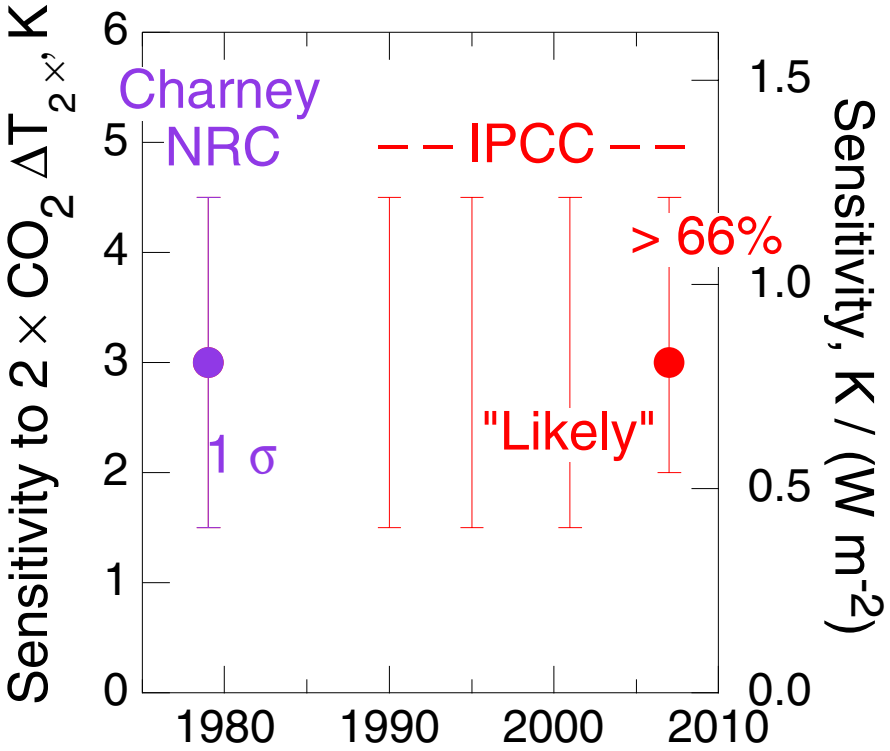
Sensitivity is commonly expressed as "CO_2 doubling temperature"

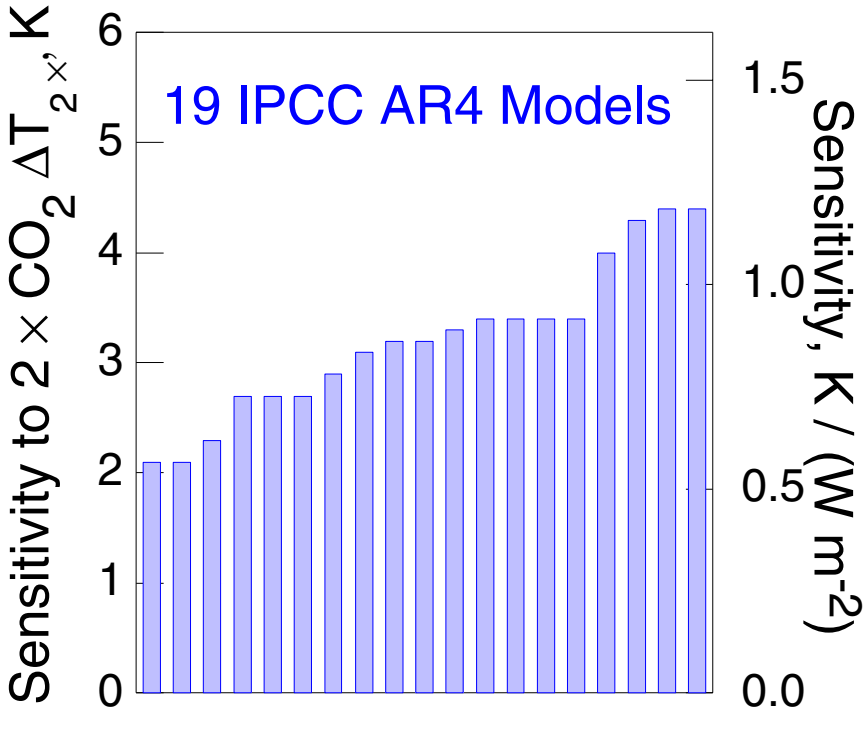
$$\Delta T_{2\times} \equiv S \times F_{2\times}$$

where $F_{2\times}$ is the "CO_2 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 CO_2 doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty.

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

HOW MUCH WARMING IS EXPECTED?

For increases in CO_2, CH_4, N_2O, and CFCs over the industrial period

$$F = 2.6 \text{ W m}^{-2}$$

IPCC, 2007
Best Estimate

Expected temperature increase:

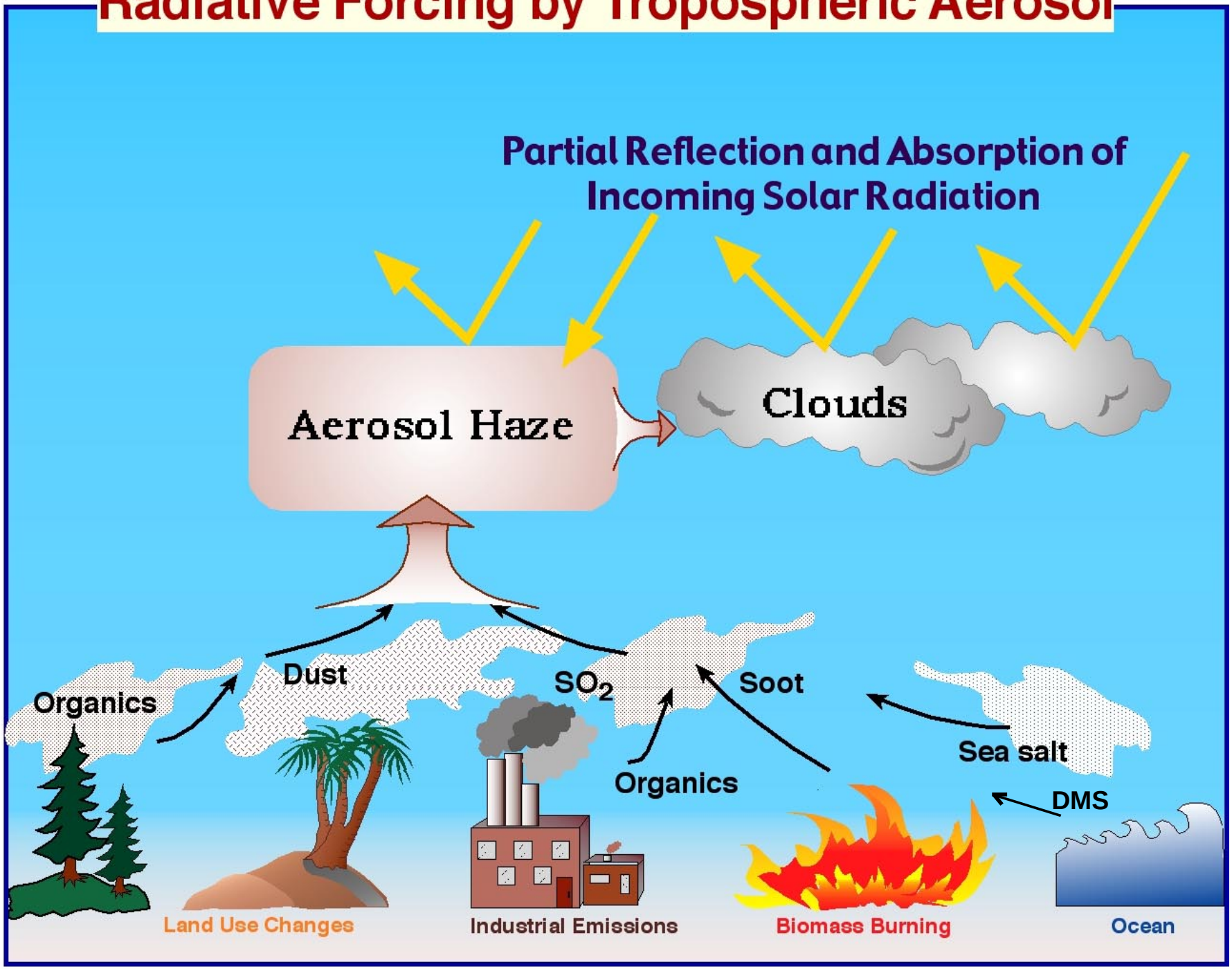
$$\Delta T_{\text{exp}} = \frac{F}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.6}{3.7} \times 3 \text{ K} = 2.1 \text{ K}$$

Observed temperature increase:

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

Warming
Discrepancy

Radiative Forcing by Tropospheric Aerosol

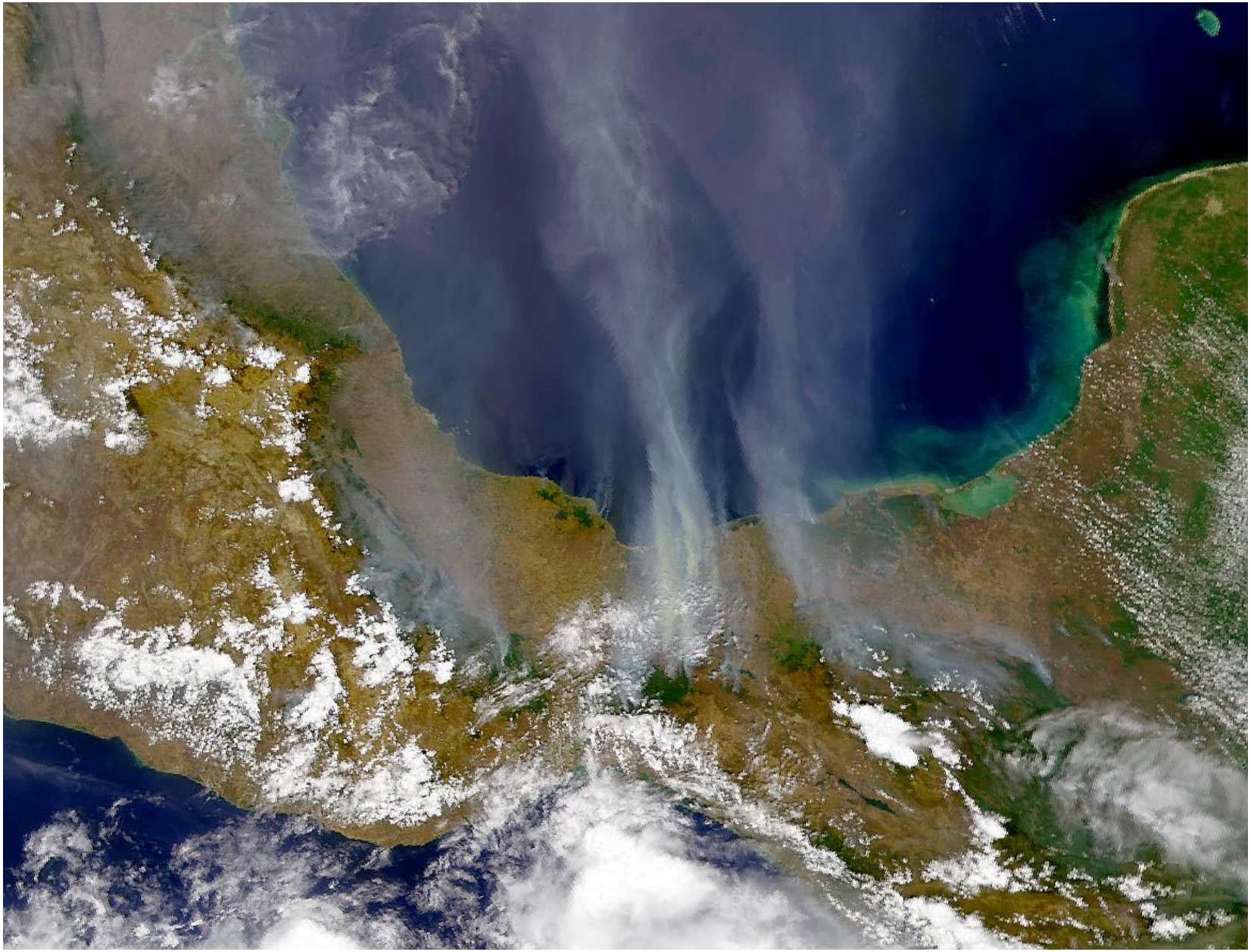


AEROSOL IN MEXICO CITY BASIN

AEROSOL IN MEXICO CITY BASIN

Light scattering by aerosols decreases absorption of solar radiation.

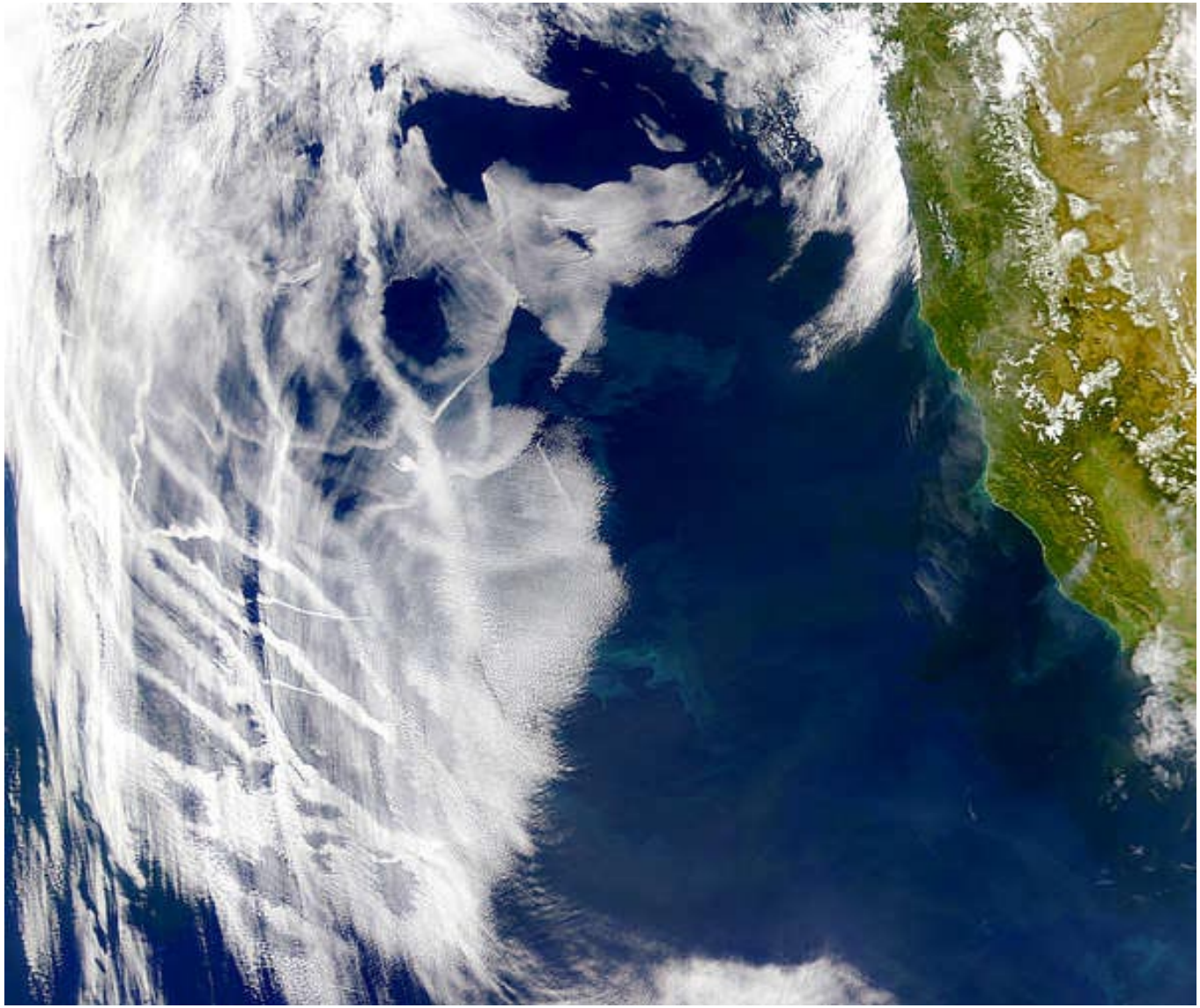
AEROSOLS AS SEEN FROM SPACE



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

CLOUD BRIGHTENING BY SHIP TRACKS

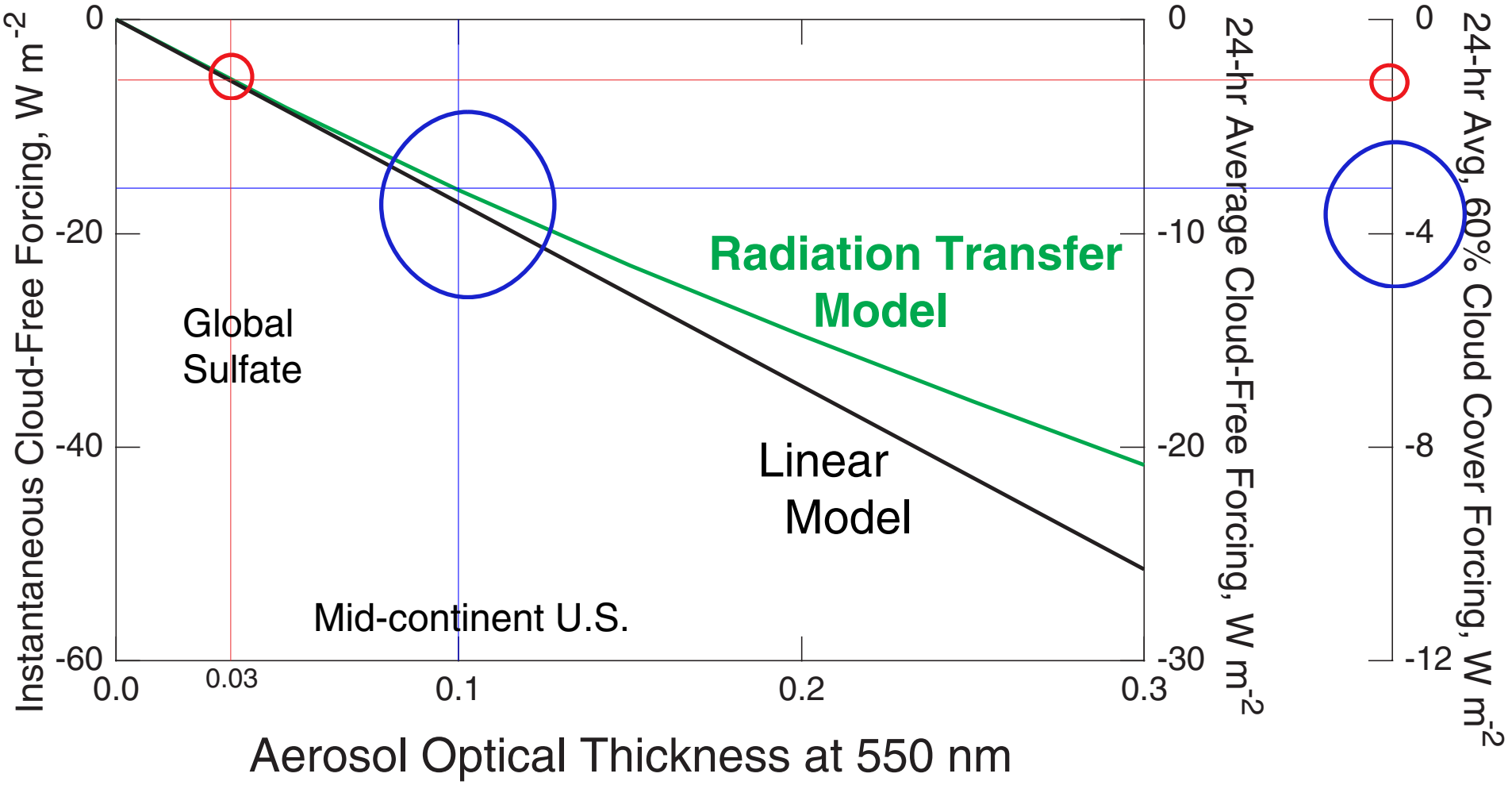
Satellite photo off California coast



Aerosols from ship emissions enhance reflectivity of marine stratus.

ESTIMATES OF AEROSOL DIRECT FORCING

By linear model and by radiation transfer modeling

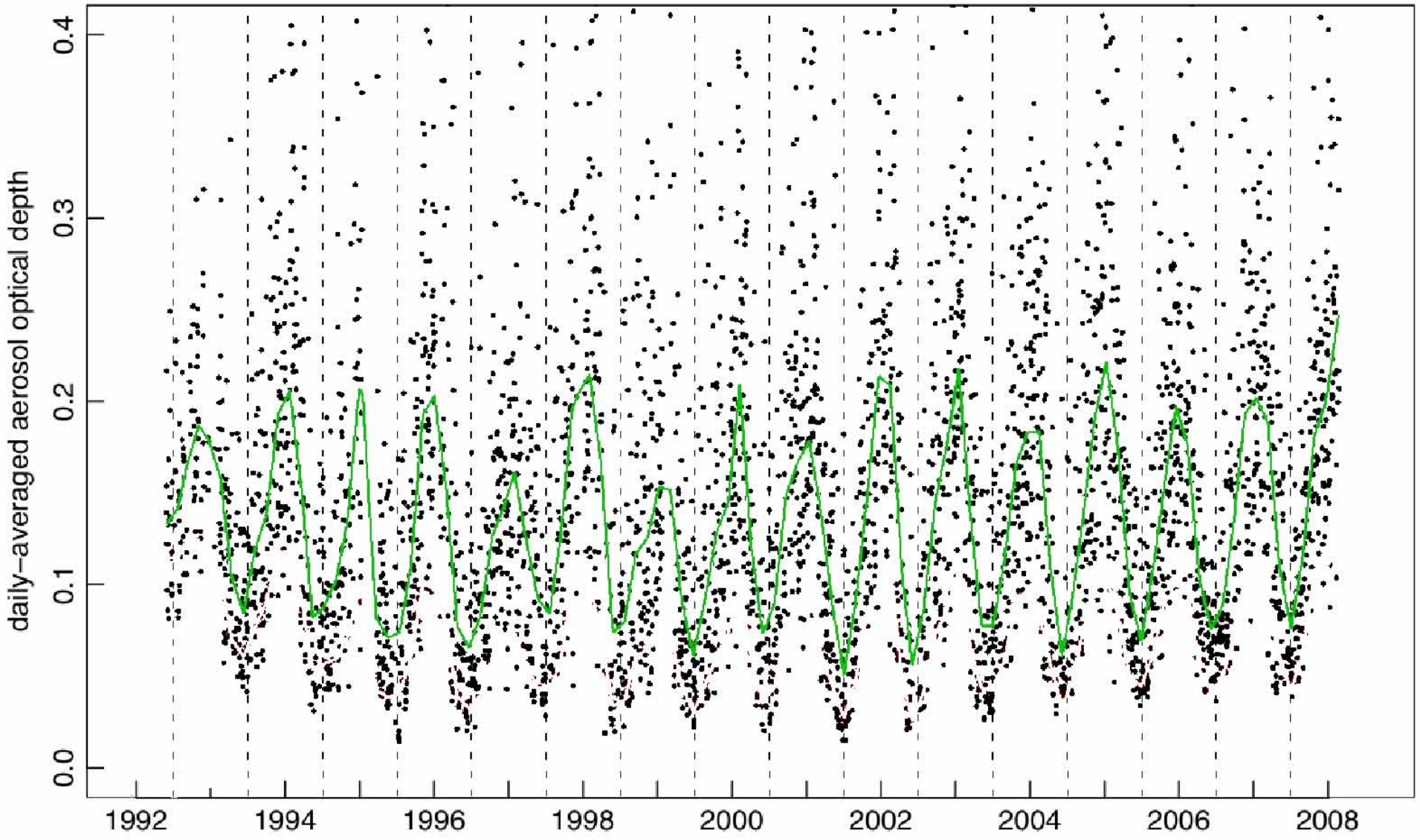


Global average sulfate optical thickness is 0.03: ***1 W m^{-2} cooling.***

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

AEROSOL OPTICAL DEPTH AT ARM SGP

Fifteen years of daily average 500 nm AOD in North Central Oklahoma

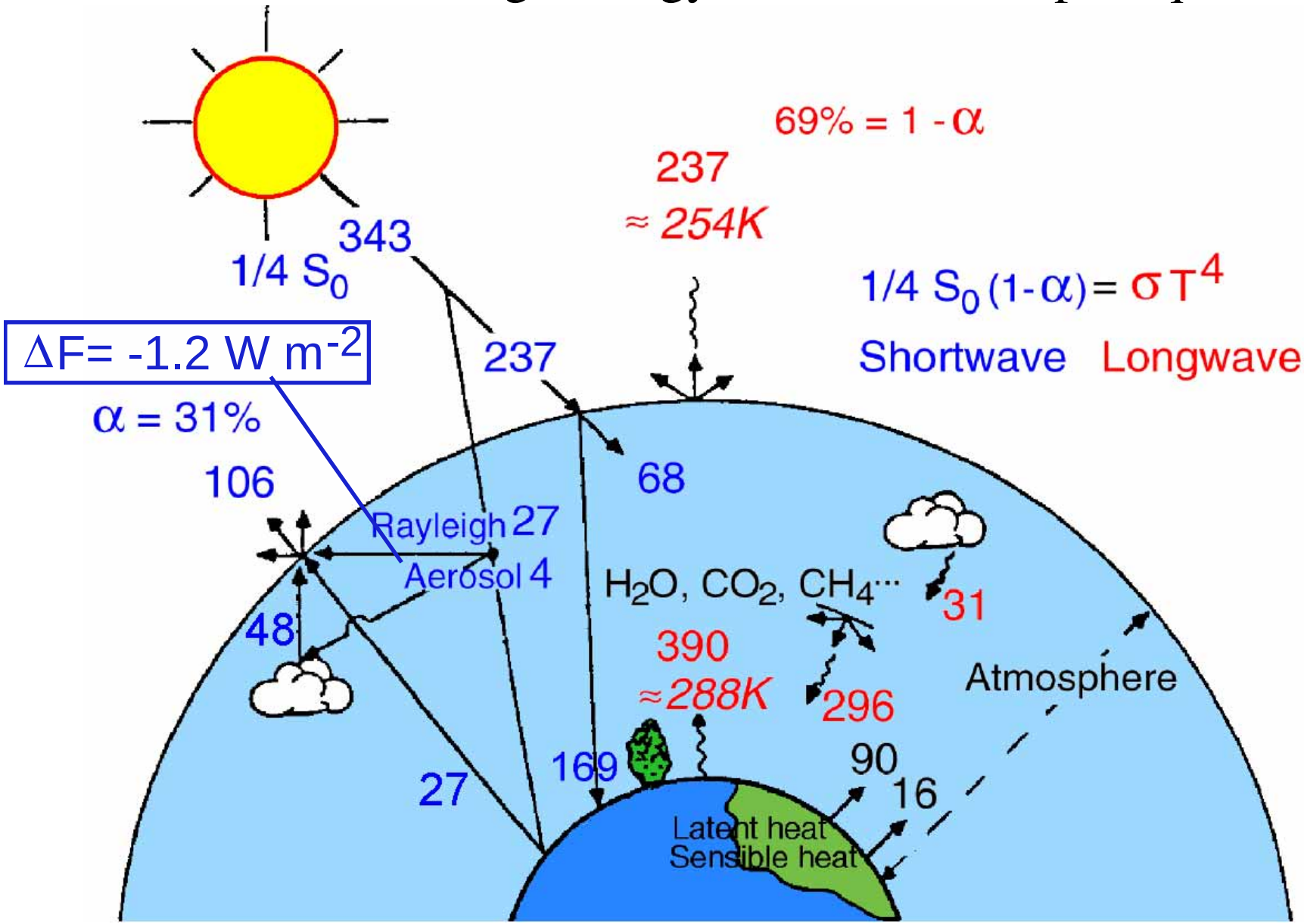


Michalsky, Denn, Flynn, Hodges, Kiedron, Koontz, Schlemmer, Schwartz, JGR, 2010

Green curve is LOWESS (locally weighted scatterplot smoothing) fit.

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

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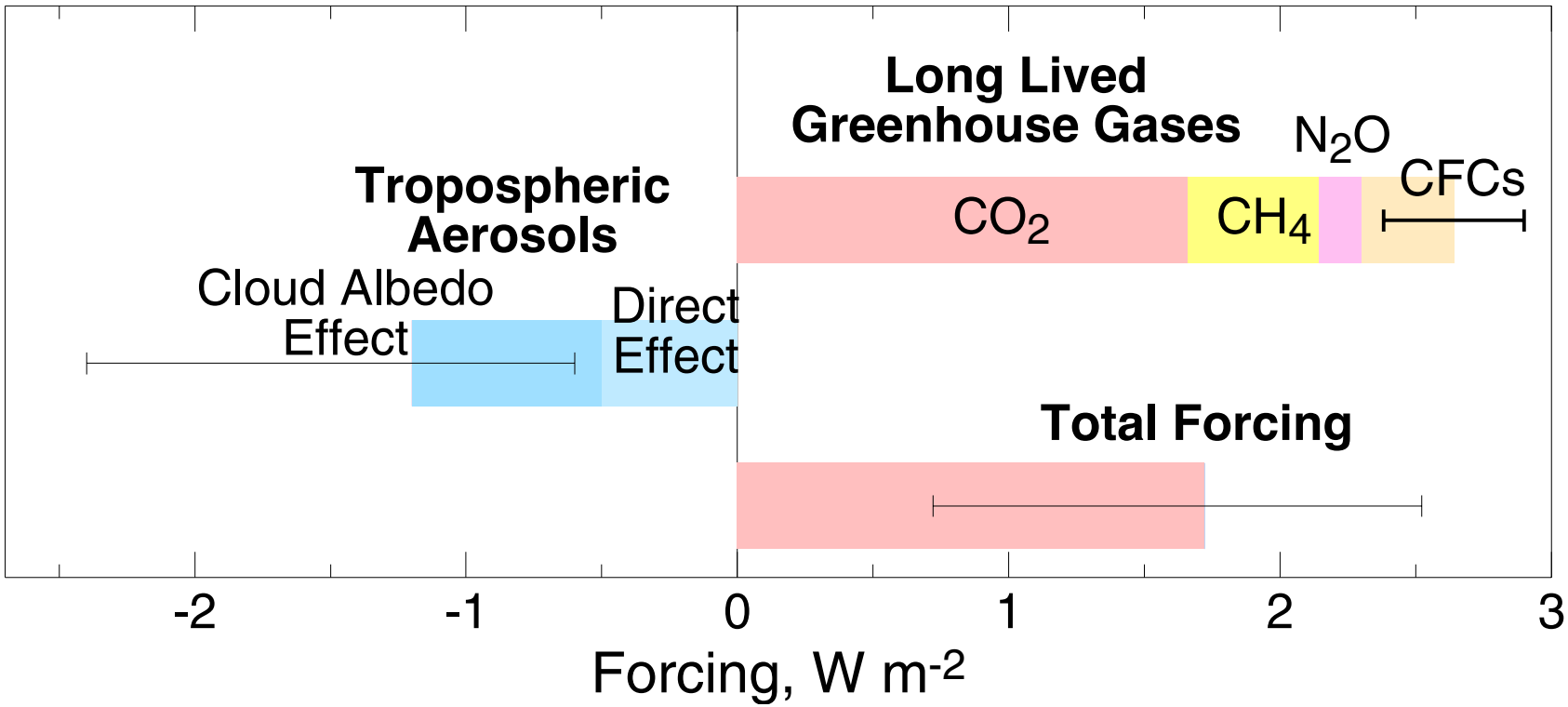


Total forcing includes other anthropogenic and natural (solar) forcings.

Forcing by tropospheric ozone, ~0.35 W m^{-2}, is the greatest of these.

Uncertainty in aerosol forcing dominates uncertainty in total forcing.

THE PATH FORWARD

Determine aerosol forcing with high accuracy.

Multiple approaches are required:

Laboratory studies of aerosol processes.

Field measurements of aerosol processes and properties: emissions, new particle formation, evolution, size distributed composition, optical properties, CCN properties, removal processes . . .

Represent aerosol processes in ***chemical transport models***.

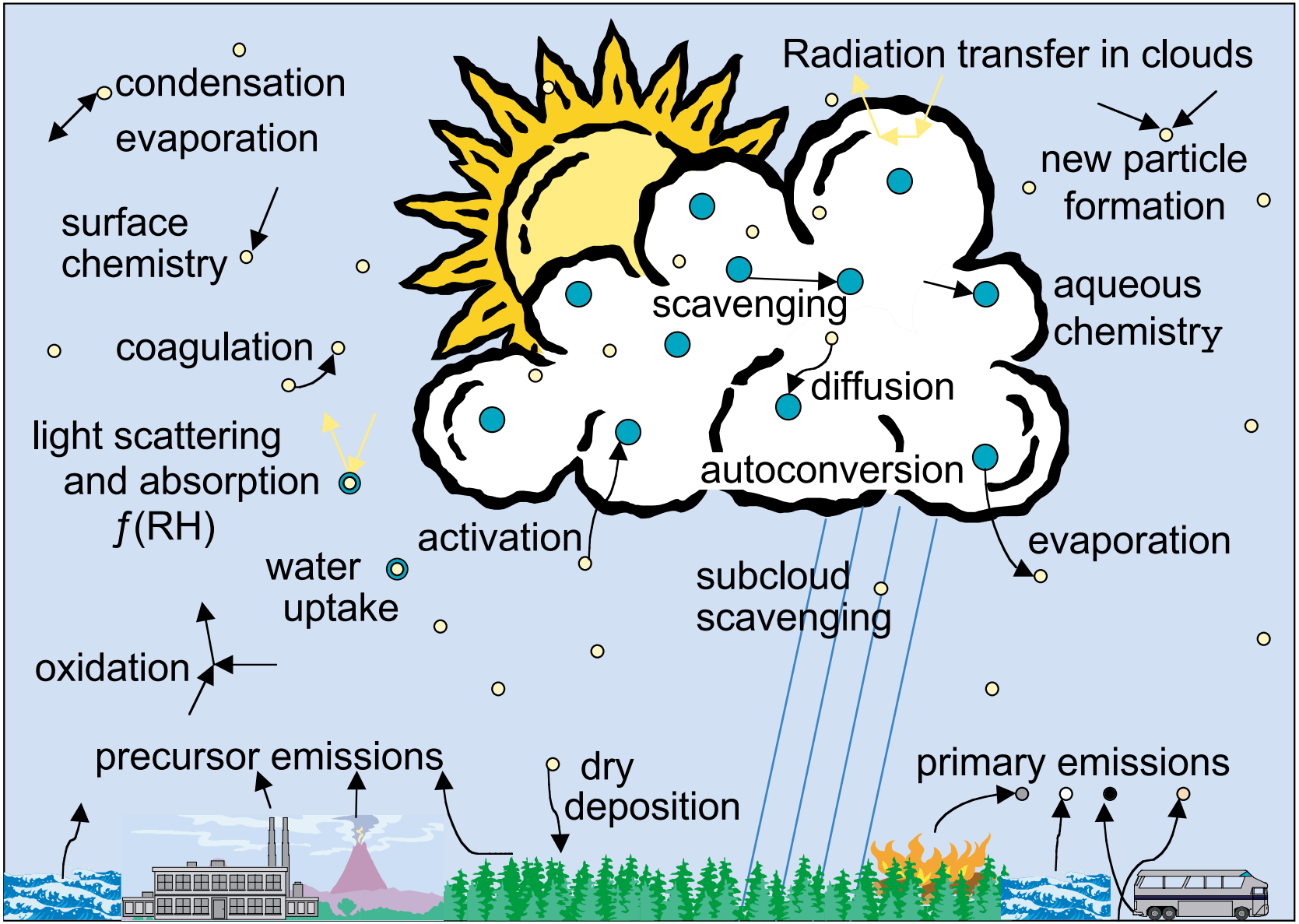
Evaluate models by ***comparison with observations***.

Satellite measurements for spatial coverage.

Calculate forcings in ***chemical transport models and GCMs***.

Measurement based determination of aerosol forcings.

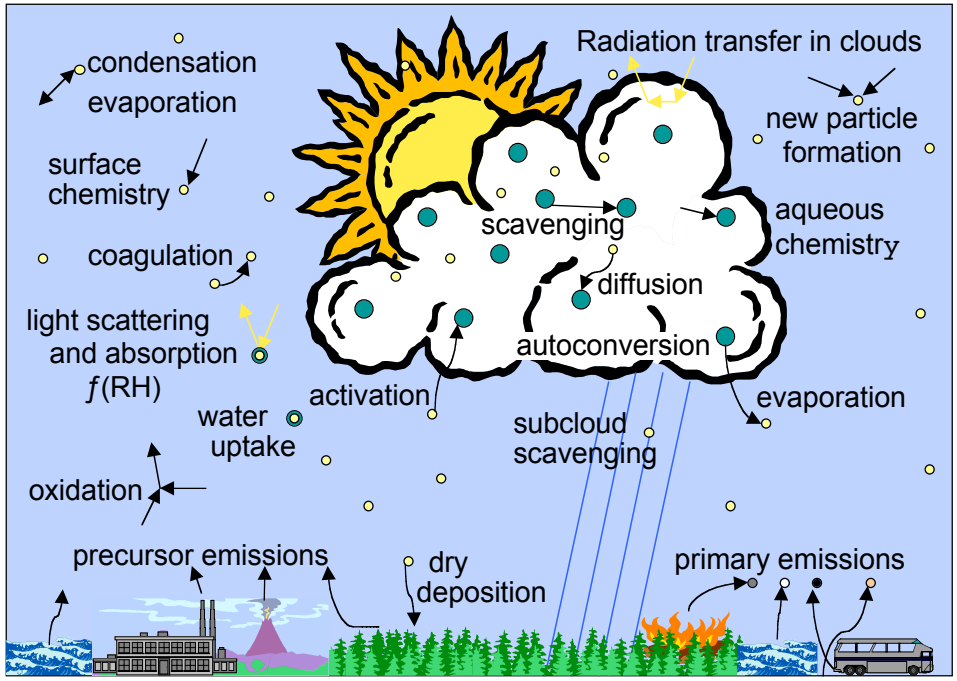
AEROSOL PROCESSES THAT MUST BE UNDERSTOOD AND REPRESENTED IN MODELS

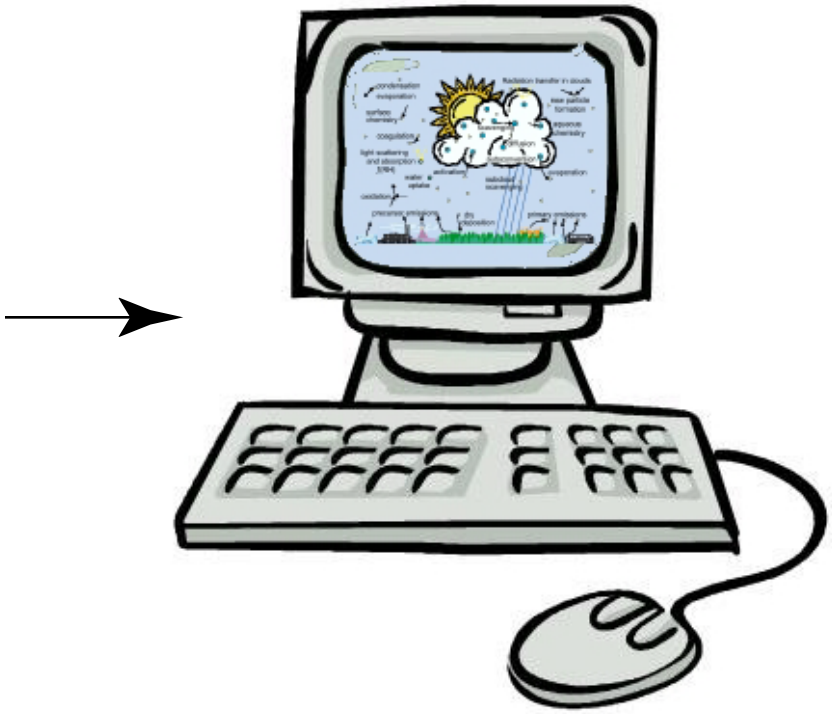


Modified from Ghan and Schwartz, Bull. Amer. Meterol. Soc., 2007

APPROACH TO DETERMINE AEROSOL FORCING

Numerical simulation of physical processes





Isomorphism of processes to computer code

Modeling aerosol processes requires understanding these processes, developing and testing their numerical representations, and incorporating these representations in global scale models.