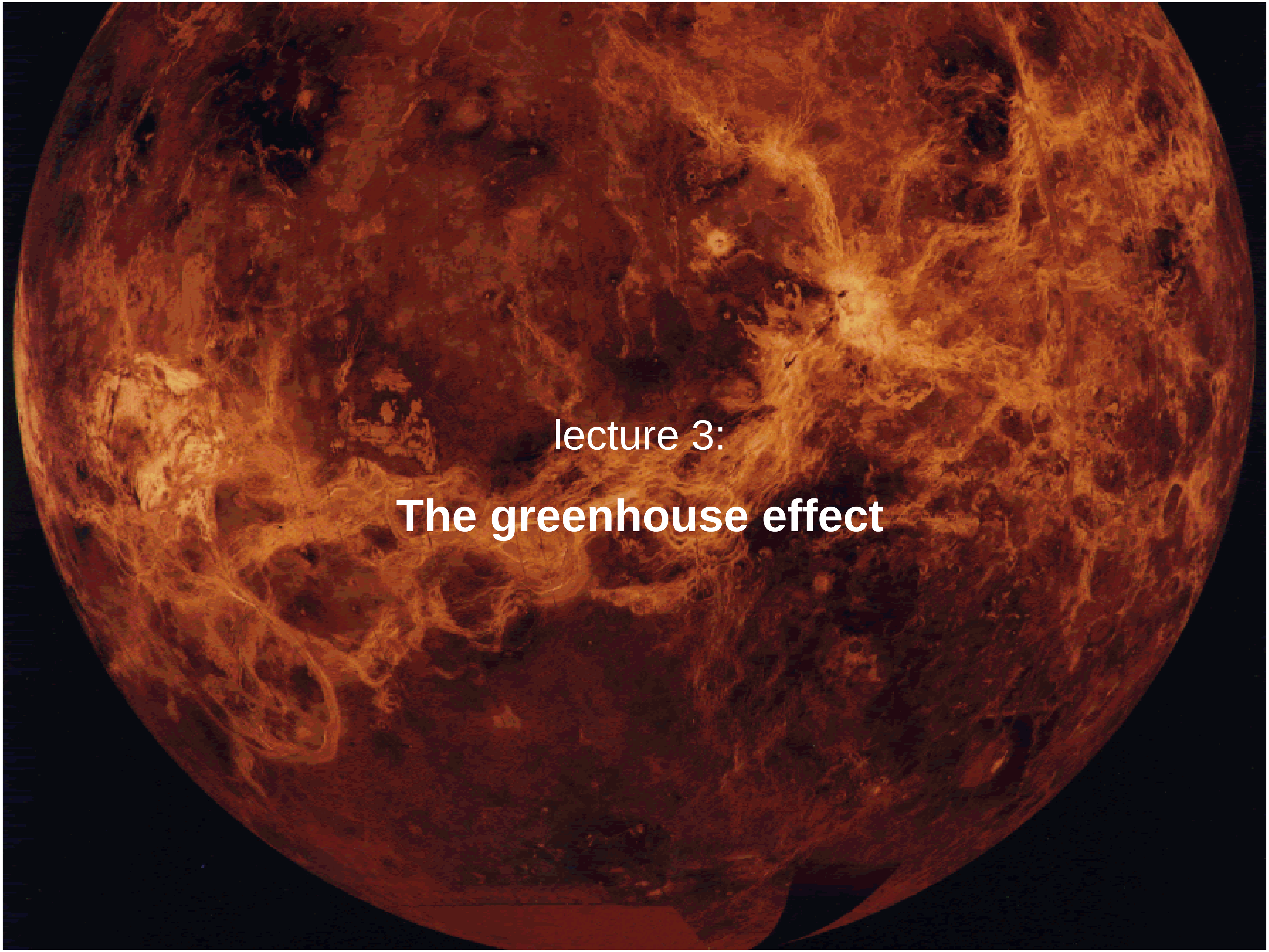


lecture 3:

The greenhouse effect

Concepts from Lecture 2

Temperature Scales

Forms of Heat Transfer

Electromagnetic Spectrum

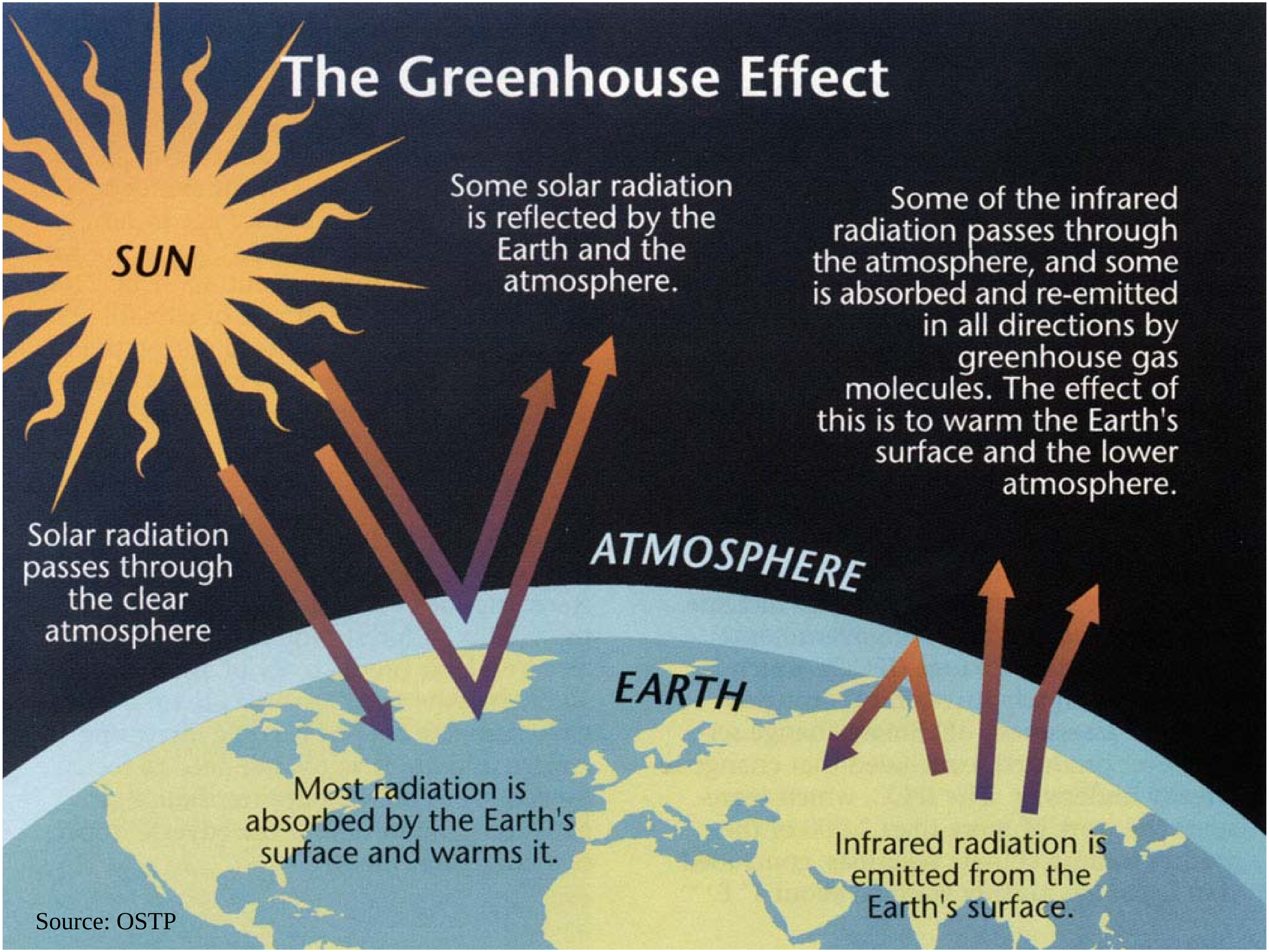
Planck Law

Stefan-Boltzmann Law

Inverse Square Law

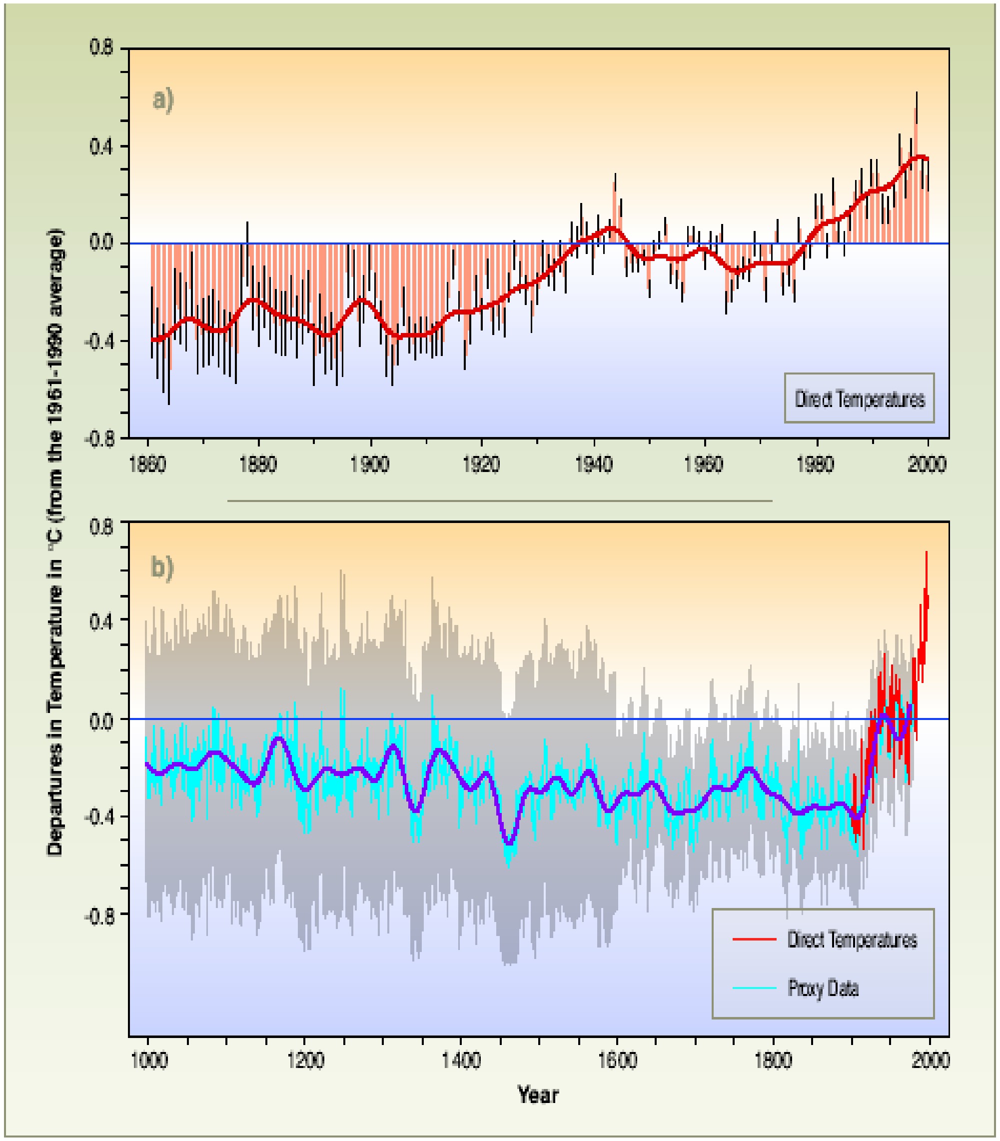
Reflectivity or Albedo

Solar (Shortwave) and Terrestrial (Longwave) Radiation

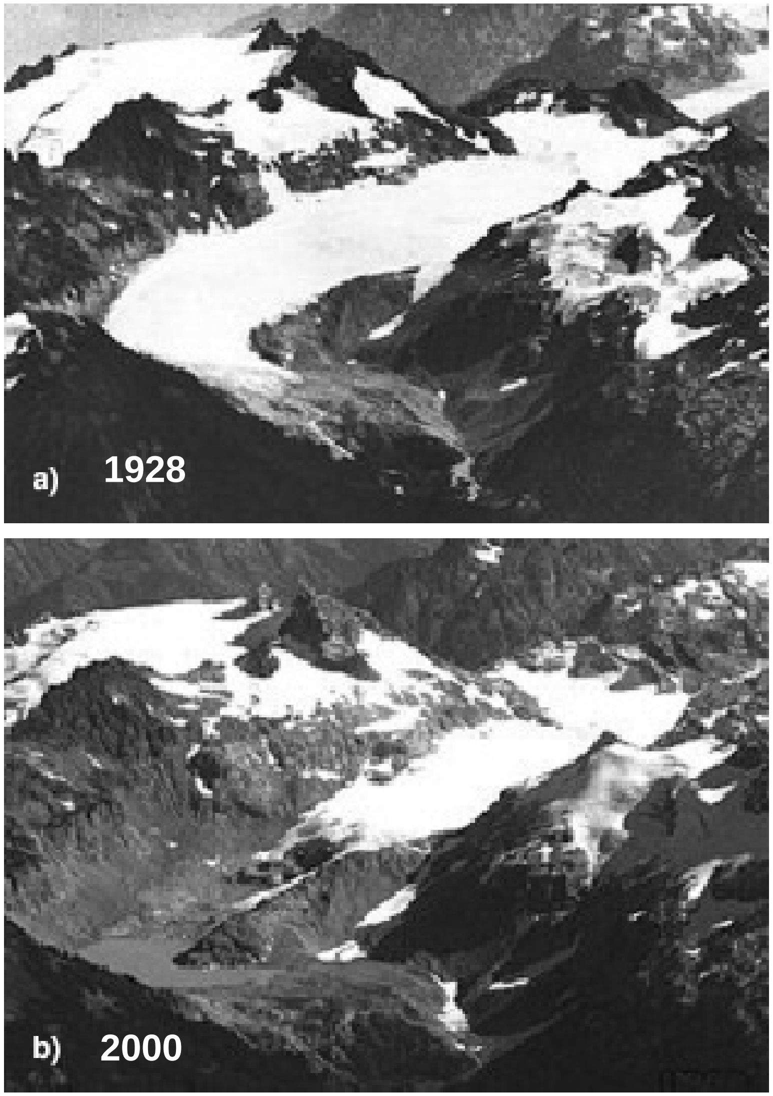

The Greenhouse Effect
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower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

Source: OSTP

Strong Evidence for Global Warming

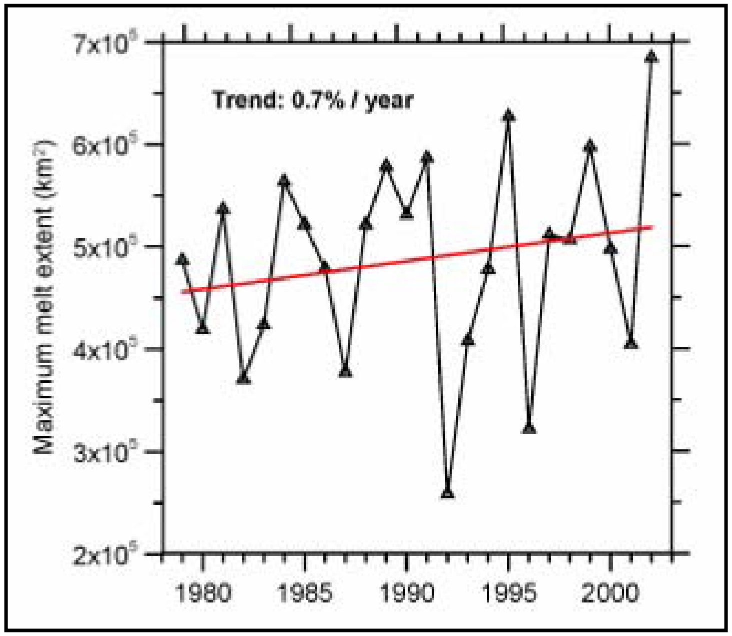


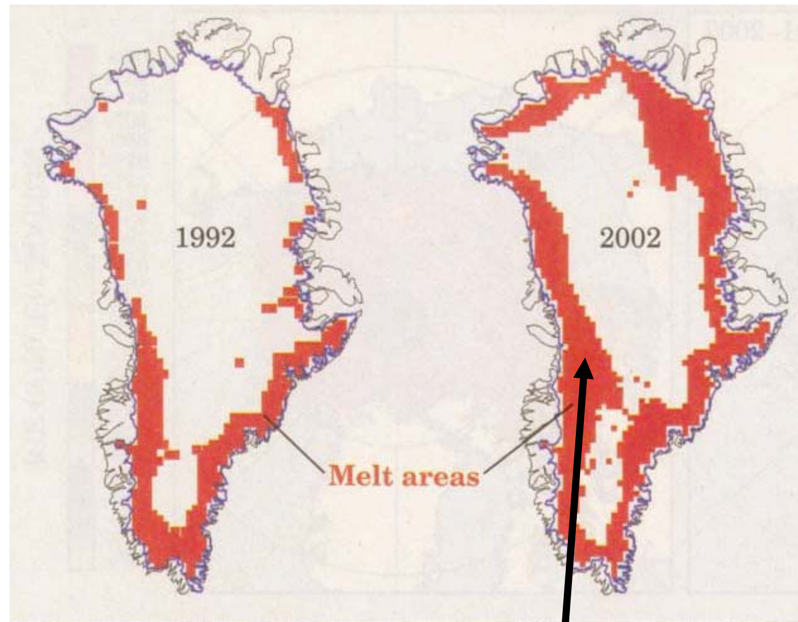
From US Climate Change Science Program



South Cascade Glacier, Washington

Increasing Melt Area on Greenland



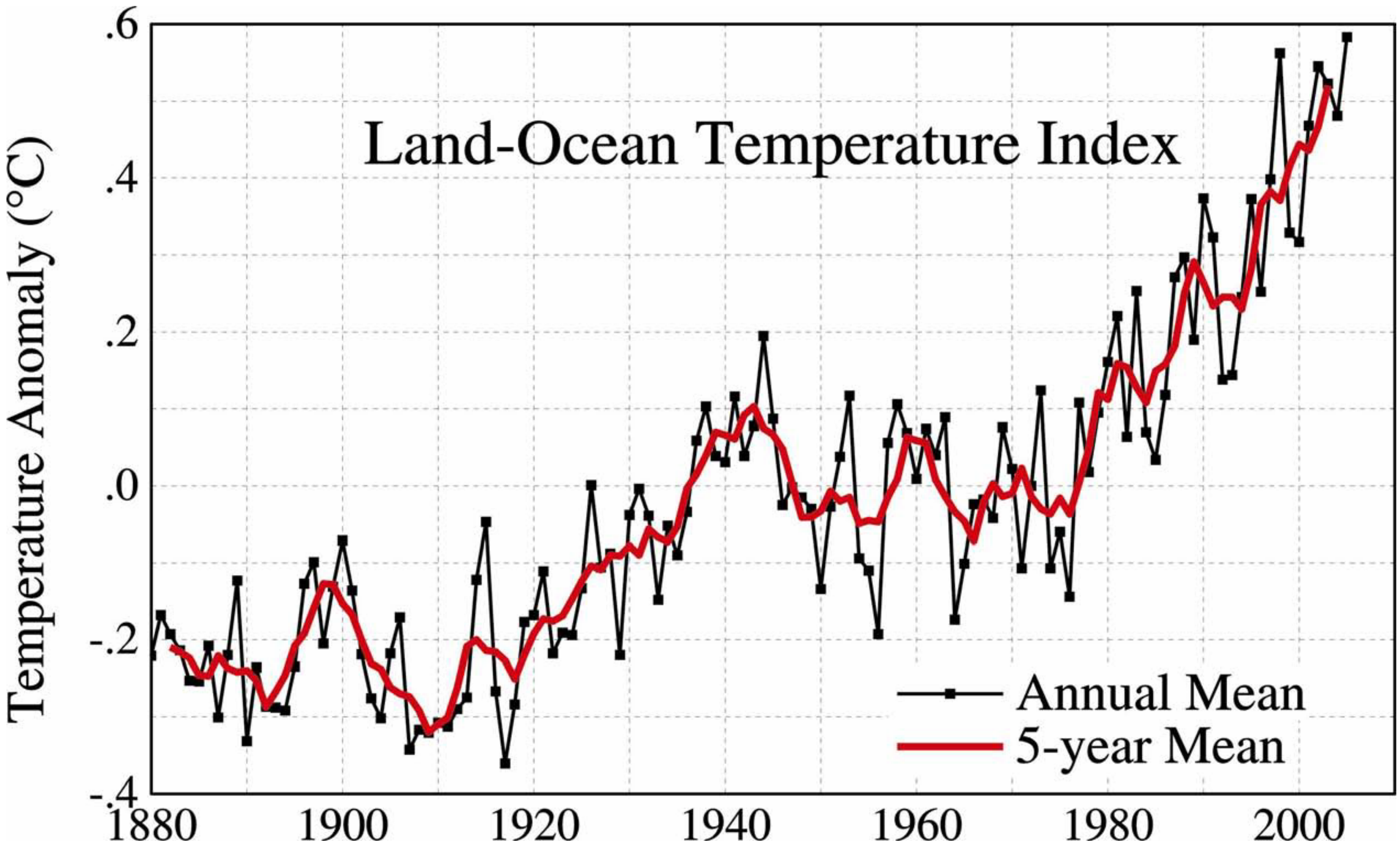


- 2002 all-time record melt area
- Melting up to elevation of 2000 m
- 16% increase from 1979 to 2002

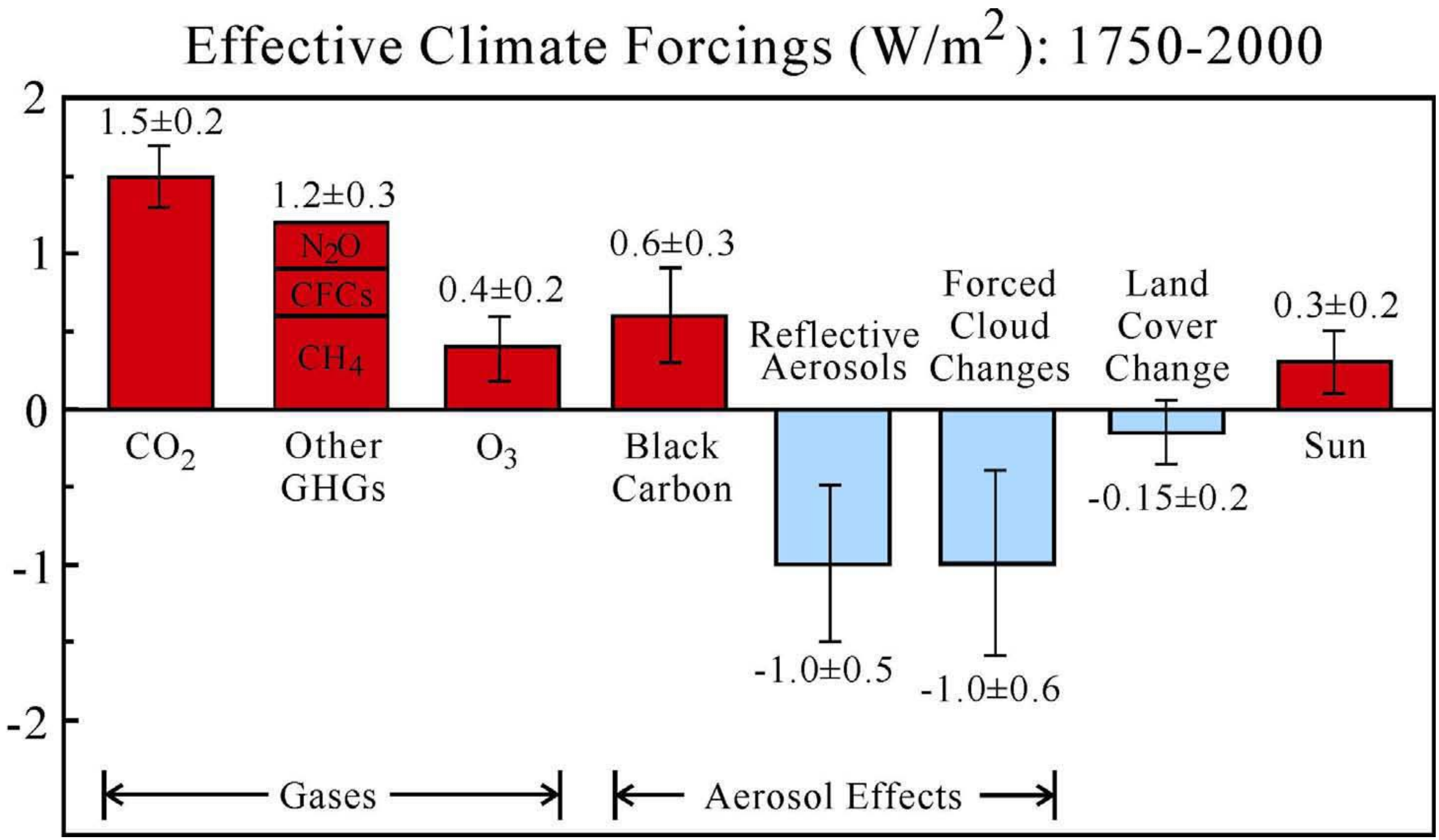
70 meters thinning in 5 years

Satellite-era record melt of 2002 was exceeded in 2005.

Source: Waleed Abdalati, Goddard Space Flight Center



Global mean surface temperature change based on surface air measurements over land and SSTs over ocean. *Source:* Update of Hansen et al., *JGR,* 106, 23947, 2001; Reynolds and Smith, *J. Climate,* 7, 1994;Rayner et al., *JGR,* 108, 2003 (afterJames E.Hansen 2006).



Climate forcing agents in the industrial era. “Effective” forcing accounts for “efficacy” of the forcing mechanism

Source: Hansen et al., JGR, **110**, D18104, 2005.

The greenhouse effect of Venus

From geometry, we can calculate the average solar flux over the surface of Venus. It is approximately **661 W/m^2**.

Venus is very reflective of solar radiation. In fact, it has a reflectivity (or albedo) of 0.8, so the planet absorbs approximately 661 X 0.2 = **132 W/m^2**.

By assuming that the incoming radiation equals the outgoing radiation (**energy balance**), we can convert this into an effective radiating temperature by invoking the Stefan-Boltzmann law (total energy = σT^4). We find that **T=220 K**.

But Venus' surface has a temperature of **730 K**!!!

The explanation for this huge discrepancy is the planet's greenhouse effect.

The greenhouse effect of Earth

From geometry, we can calculate the average solar flux at the top of the atmosphere. It is approximately **343 W/m^2**.

The earth has a much lower albedo than Venus (0.3), so the planet absorbs approximately 343 X 0.7 = **240 W/m^2**.

By assuming that the incoming radiation equals the outgoing radiation, we can convert this into an effective radiating temperature by invoking the Stefan-Boltzmann law (total energy = σT^4). We find that **T=254 K**.

Earth's surface has a temperature of **288 K**

While much smaller than Venus' greenhouse effect, Earth's is crucial for the planet's habitability. Without the greenhouse effect, the temperature today in Los Angeles would be about 0 degrees Fahrenheit.

Main Constituents of the Earth's Atmosphere

Nitrogen	78%
Oxygen	21%
Argon	1%
Water Vapor	0-4%
Carbon Dioxide	0.037% (increasing)

Nitrogen, Oxygen, and Argon hardly interact with radiation. On the other hand water vapor and carbon dioxide both interact with infrared radiation---the type emitted by the Earth and its atmosphere.

A **greenhouse gas** is defined as a gas that absorbs significantly the radiation emitted by the Earth and its atmosphere (Infrared, IR, or longwave radiation).

Important Greenhouse Gases

(concentrations in parts per million volume)

water vapor	0.1-40,000
carbon dioxide	370
methane	1.7
nitrous oxide	0.3
ozone	0.01
chlorofluorocarbons	~0.0007

Greenhouse Gases (part 1)

- Carbon dioxide (CO_2): ~0.4% /yr, fossil fuel combustion, photosynthesis, and ocean, ~380 ppmv, present value
- Water vapor (H_2O): via temperature feedback
- Ozone (O_3): in the troposphere (~10 %)

Greenhouse Gases (related to O_3)

- Methane (CH_4): increasing human and animal populations, and change in land use (~ 1–2%/yr, ~1.7 ppmv)

$$CH_4 + 4O_2 \rightarrow CH_2O + H_2O + 2O_3 \quad (OH, NO)$$

- Nitrous Oxide (N_2O): Fossil fuel combustion and fertilizer denitrification (~ 0.2%/yr)

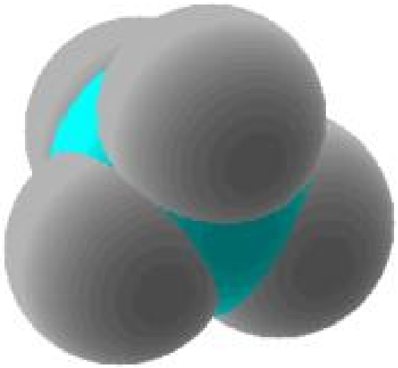
Tropophere (NO_x = NO, NO_2 , ~ O_3)

- Chlorofluorocarbons (CFCs): aerosol spray cans & refrigerant (Montreal Protocol, 1987)

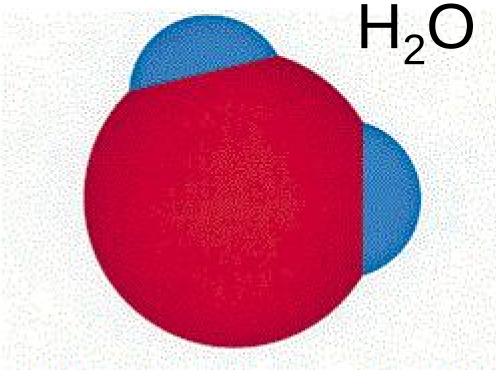
$$Cl + O_3 \rightarrow ClO + O_2 \qquad ClO + O \rightarrow Cl + O_2$$

Why do certain gases interact with radiation?

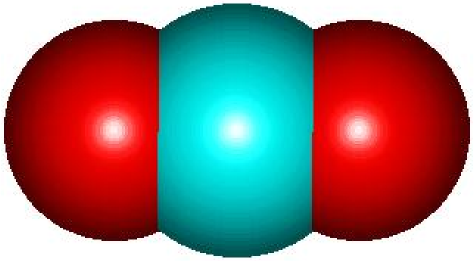
When radiation impinges on a molecule, it can excite the molecule, either by vibrating (vibrational energy) or rotating (rotational energy) it. Molecules of a particular kind of gas have a different shape from molecules of another type of gas, and so are excited by radiation in different ways.



CH_4

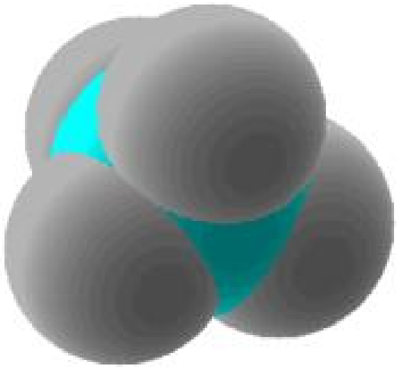


H_2O



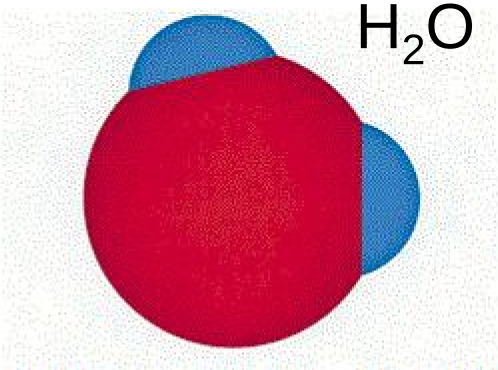
CO_2

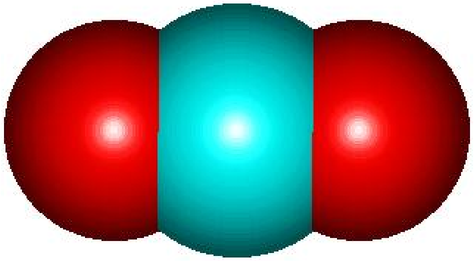
Because of their varying geometries and sizes, different molecules absorb radiation of different wavelengths. For example, CO_2 tends to absorb radiation of a wavelength of 15 μm (this wavelength excites bending vibration of the CO_2 molecule), whereas H_2O tends to absorb at wavelengths around 16-20 μm (rotation of the H_2O molecule) .



CH_4

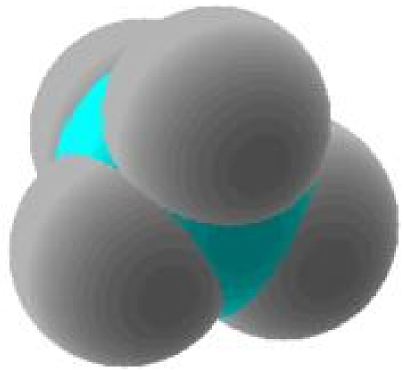
H_2O



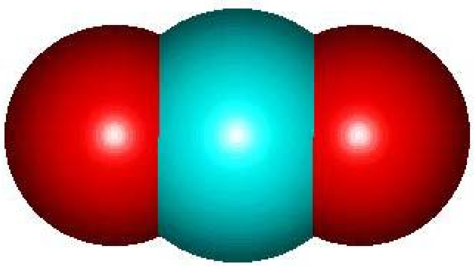


CO_2

Molecules with more than two atoms tend to absorb radiation more effectively than diatomic molecules such as N_2 and O_2. This is because of the net balance of their electron configuration. That is why diatomic nitrogen and oxygen are not greenhouse gases.

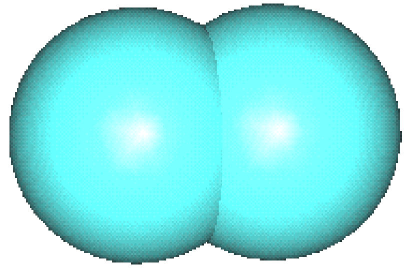


CH_4

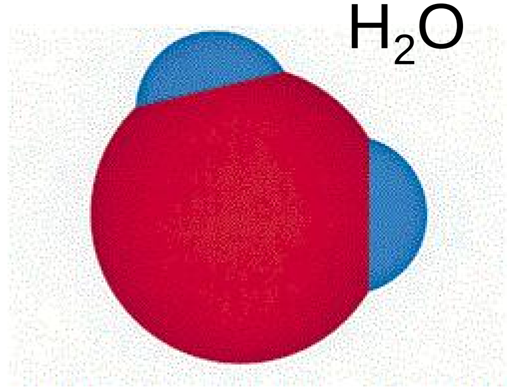


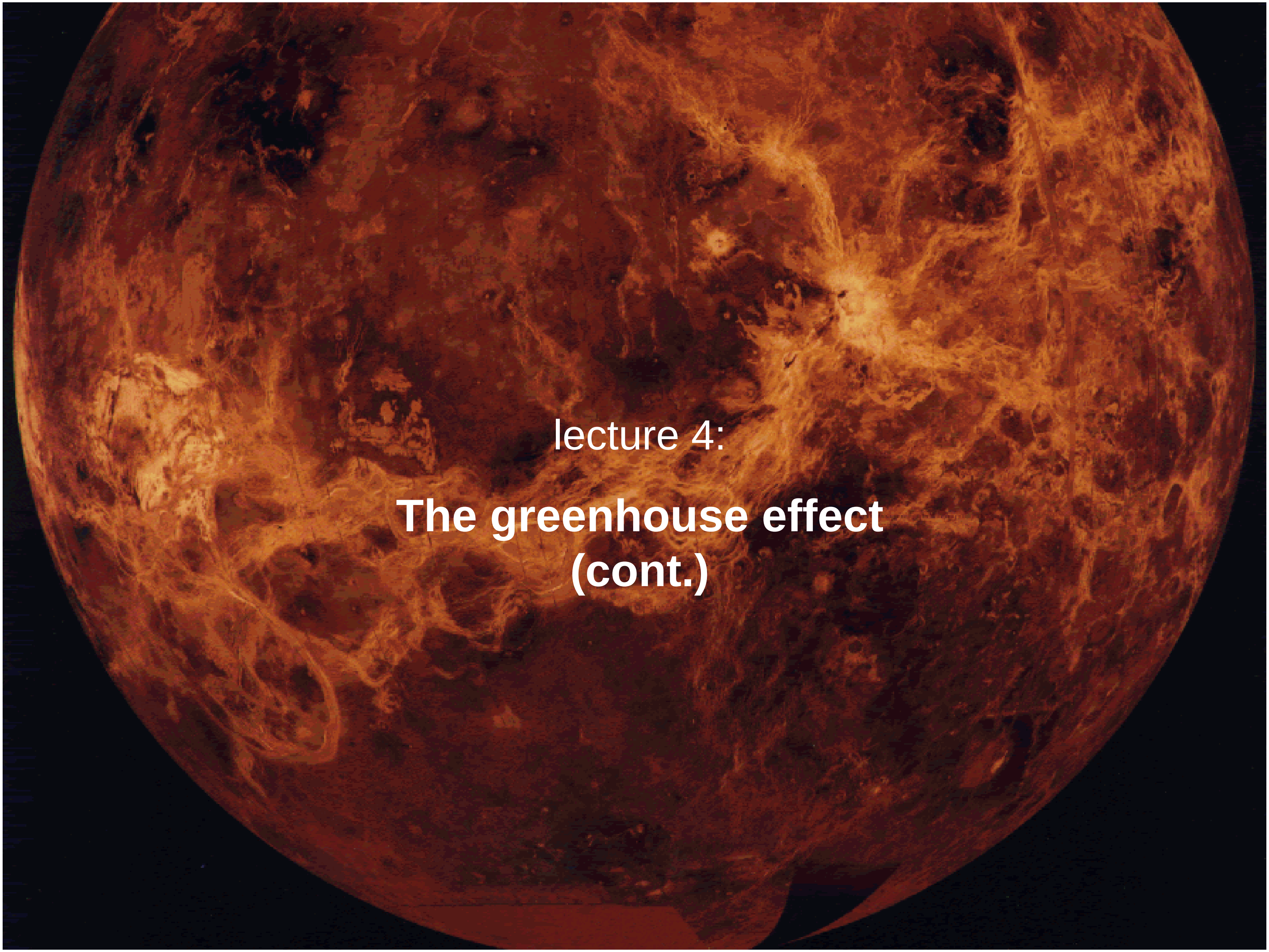
CO_2

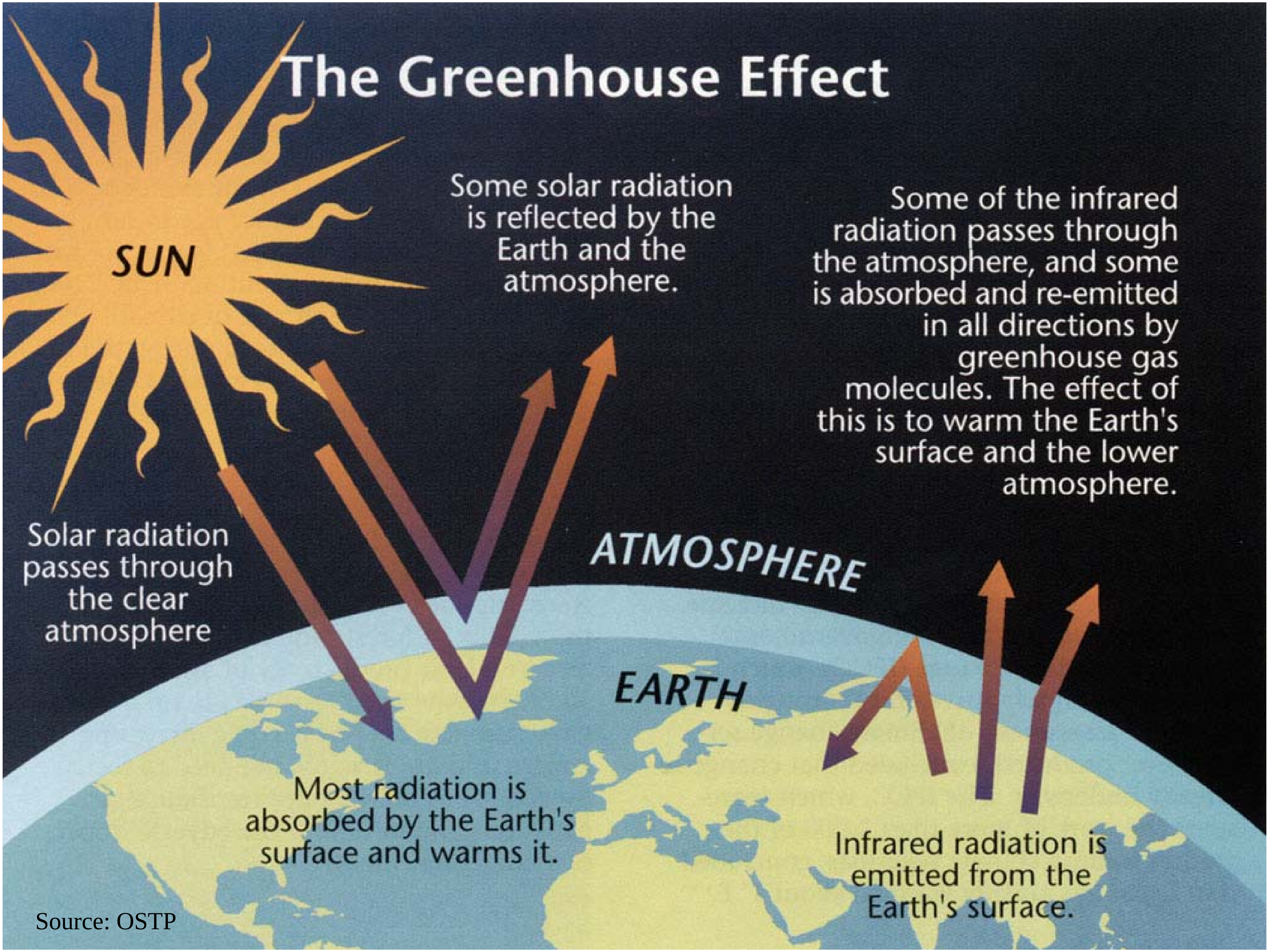
N_2, O_2



H_2O




lecture 4:
The greenhouse effect
(cont.)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Solar radiation passes through the clear atmosphere
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Infrared radiation is emitted from the Earth's surface.
Source: OSTP

A **greenhouse gas** is defined as a gas that absorbs significantly the radiation emitted by the Earth and its atmosphere (Infrared, IR, or longwave radiation).

Important Greenhouse Gases

(concentrations in parts per million volume)

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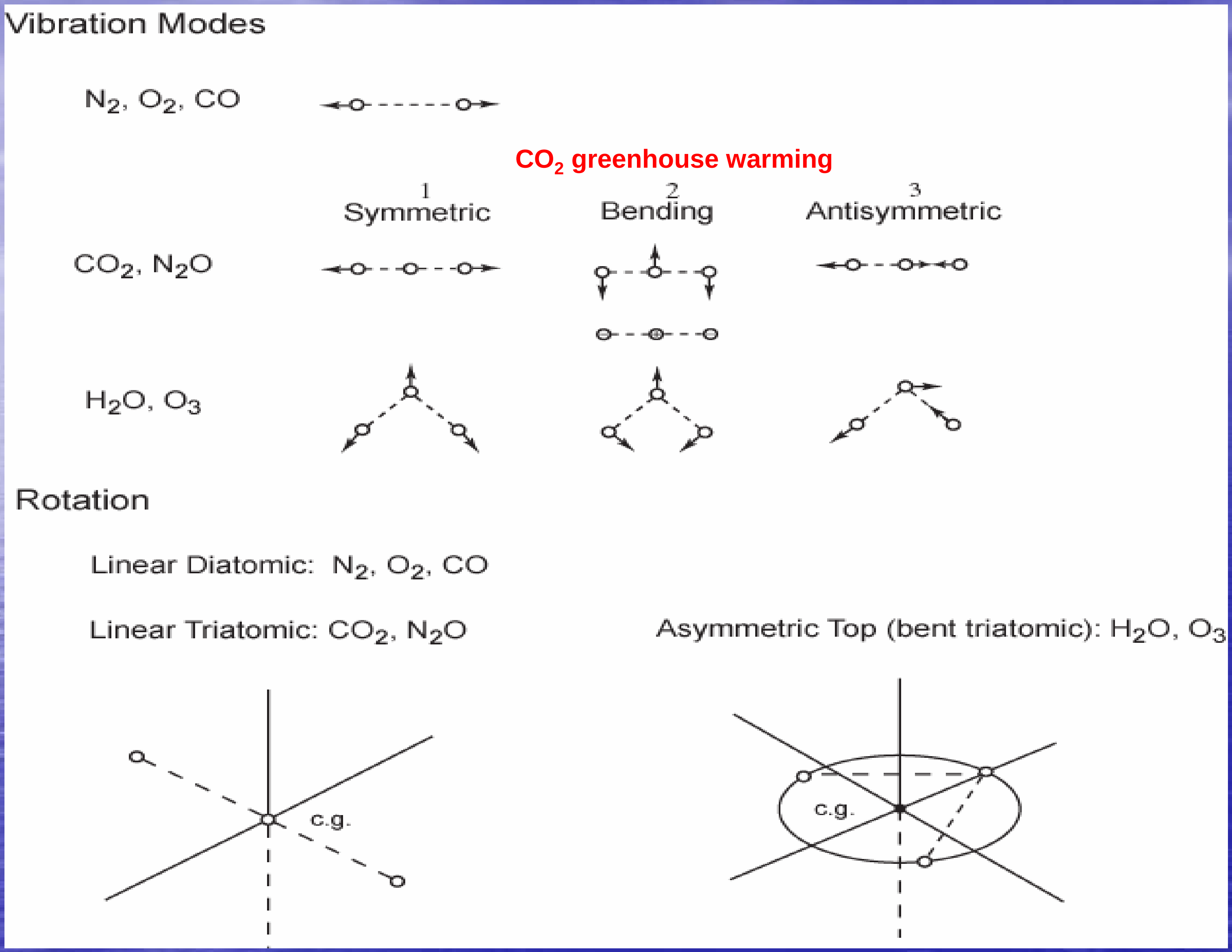


Fig. 3.3 Vibrational modes of diatomic and triatomic atmospheric molecules and the axes of rotational freedom for linear and symmetrical top molecules.

Energies of a Molecule

O----C----O

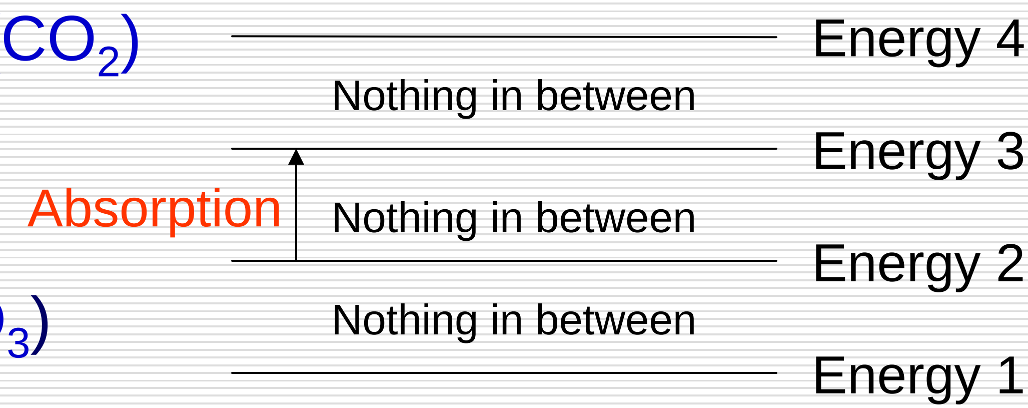
Translational energy: continuous motion (~temperature)

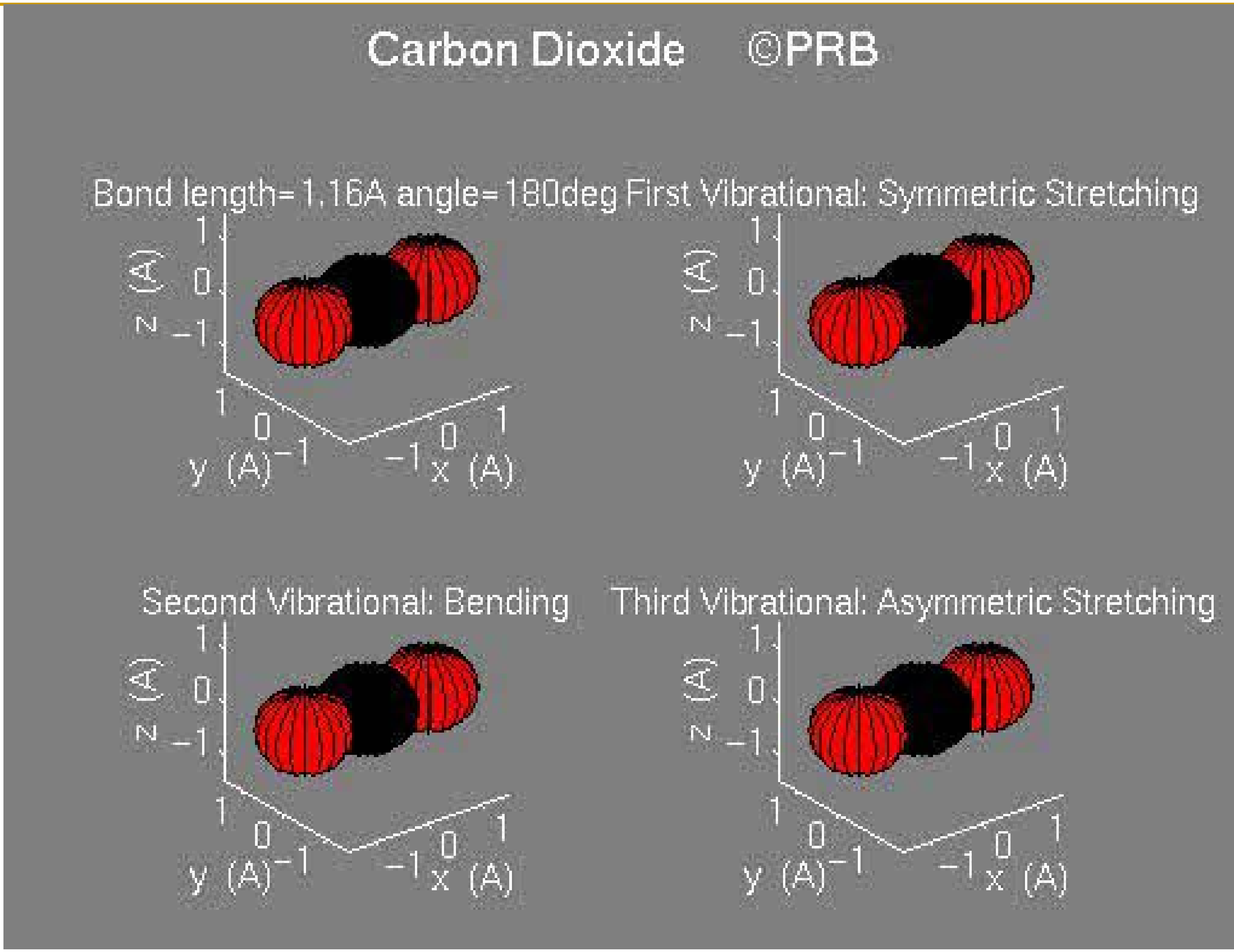
Discrete energy levels

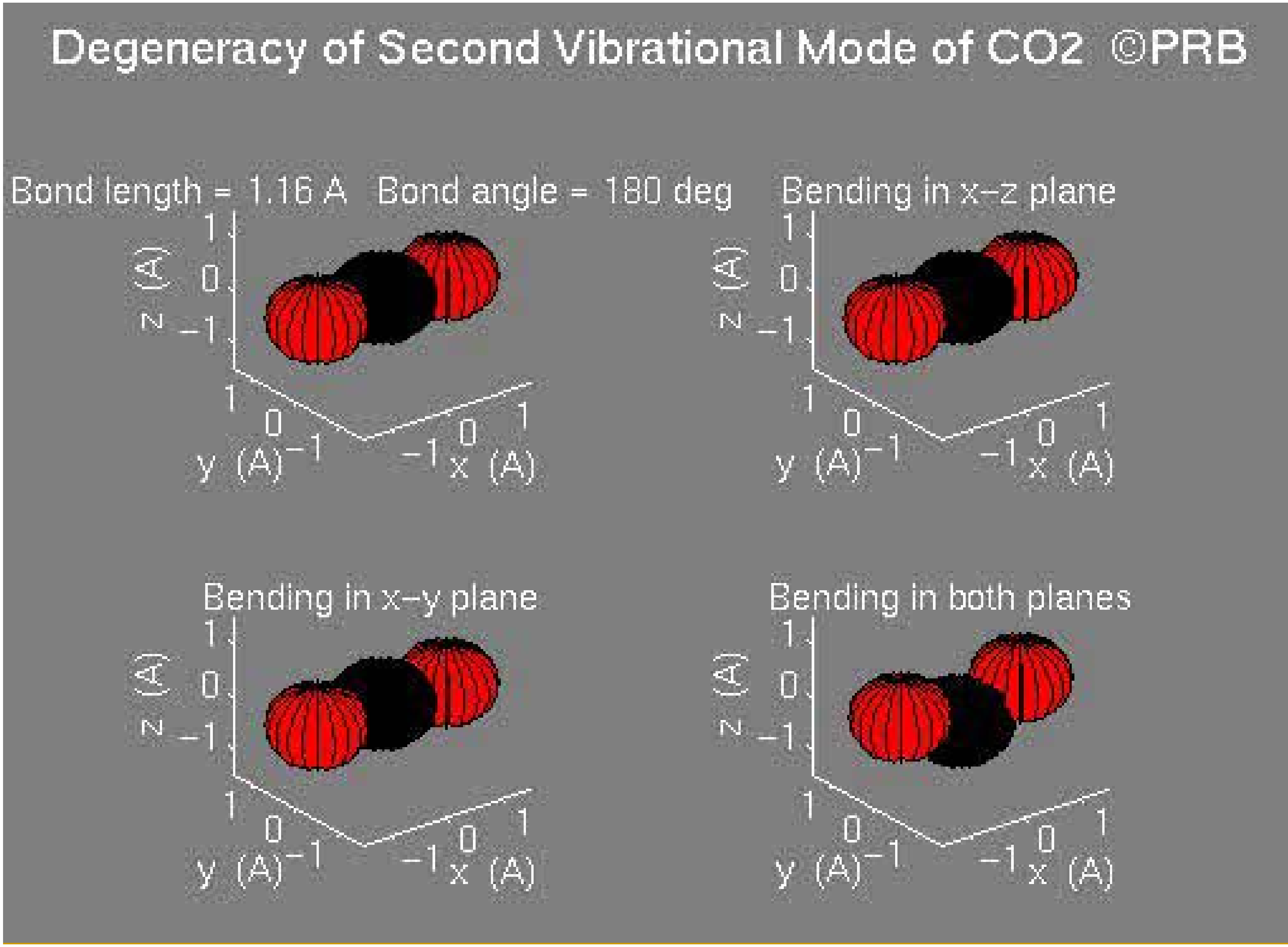
Vibrational energy
Rotational energy
} (CO_2)

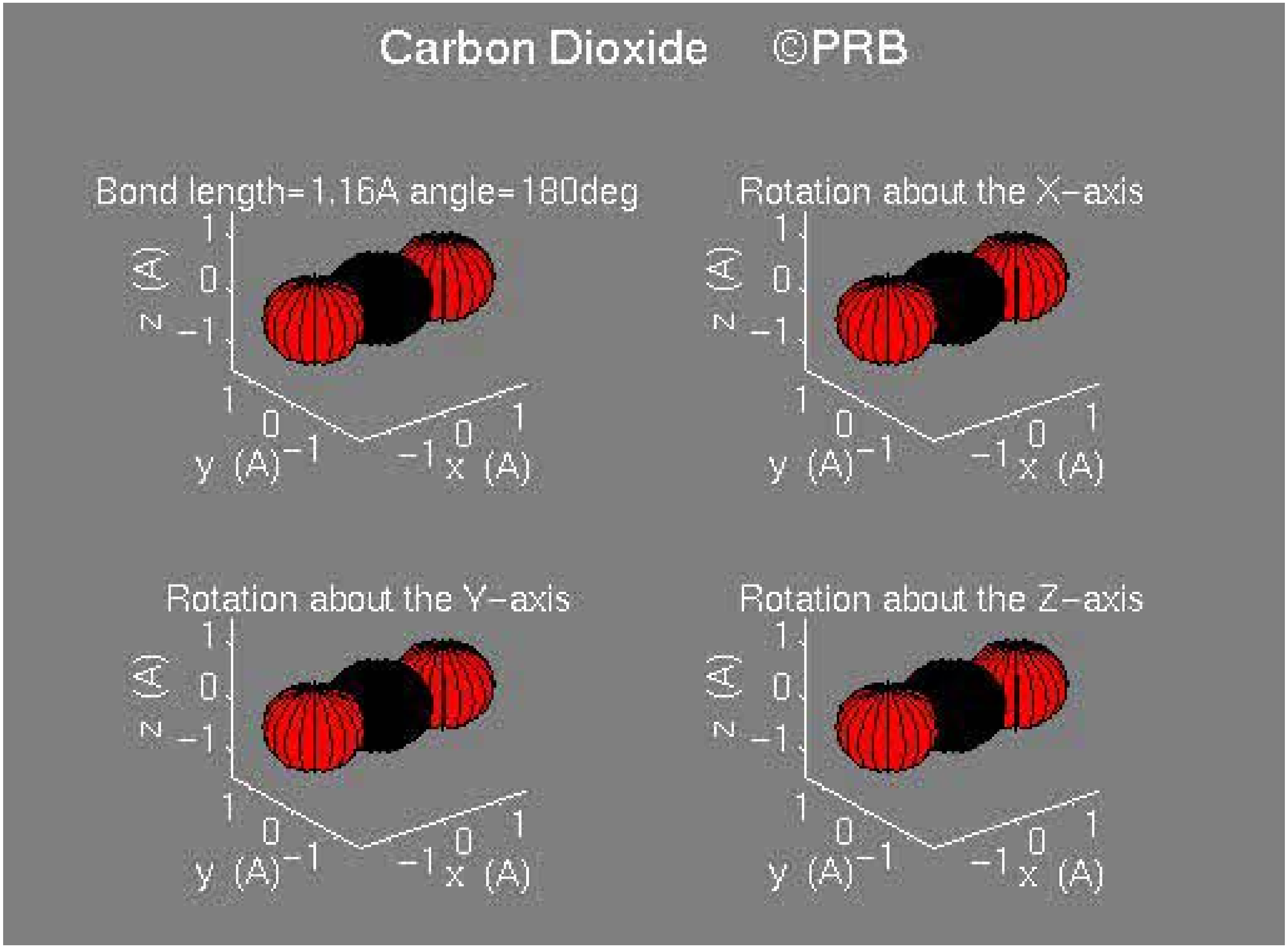
Electronic energy

(related to electrons, O_3)



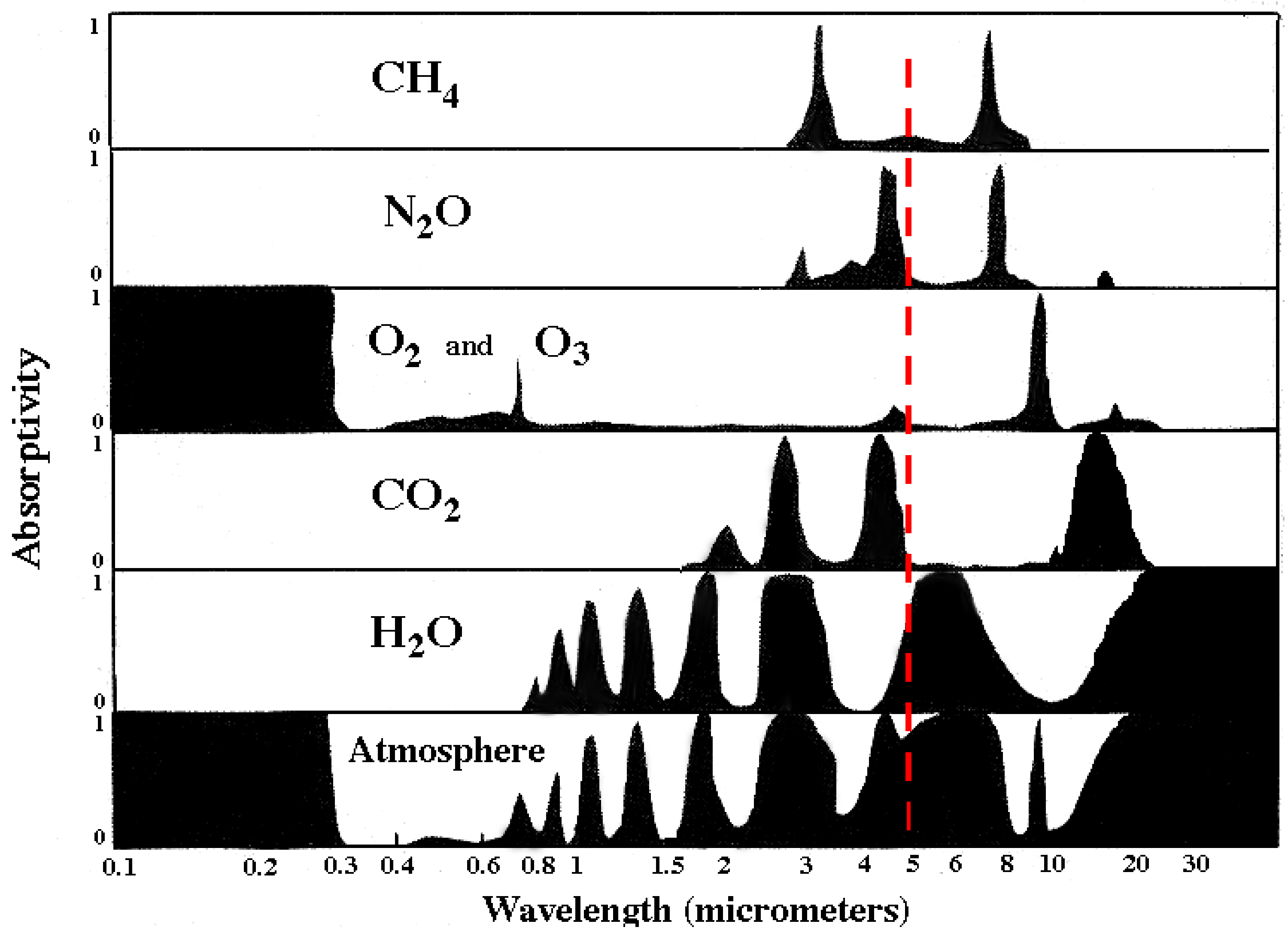

Carbon Dioxide ©PRB
Bond length=1.16A angle=180deg
First Vibrational: Symmetric Stretching
Second Vibrational: Bending
Third Vibrational: Asymmetric Stretching
z (A)
y (A)
x (A)

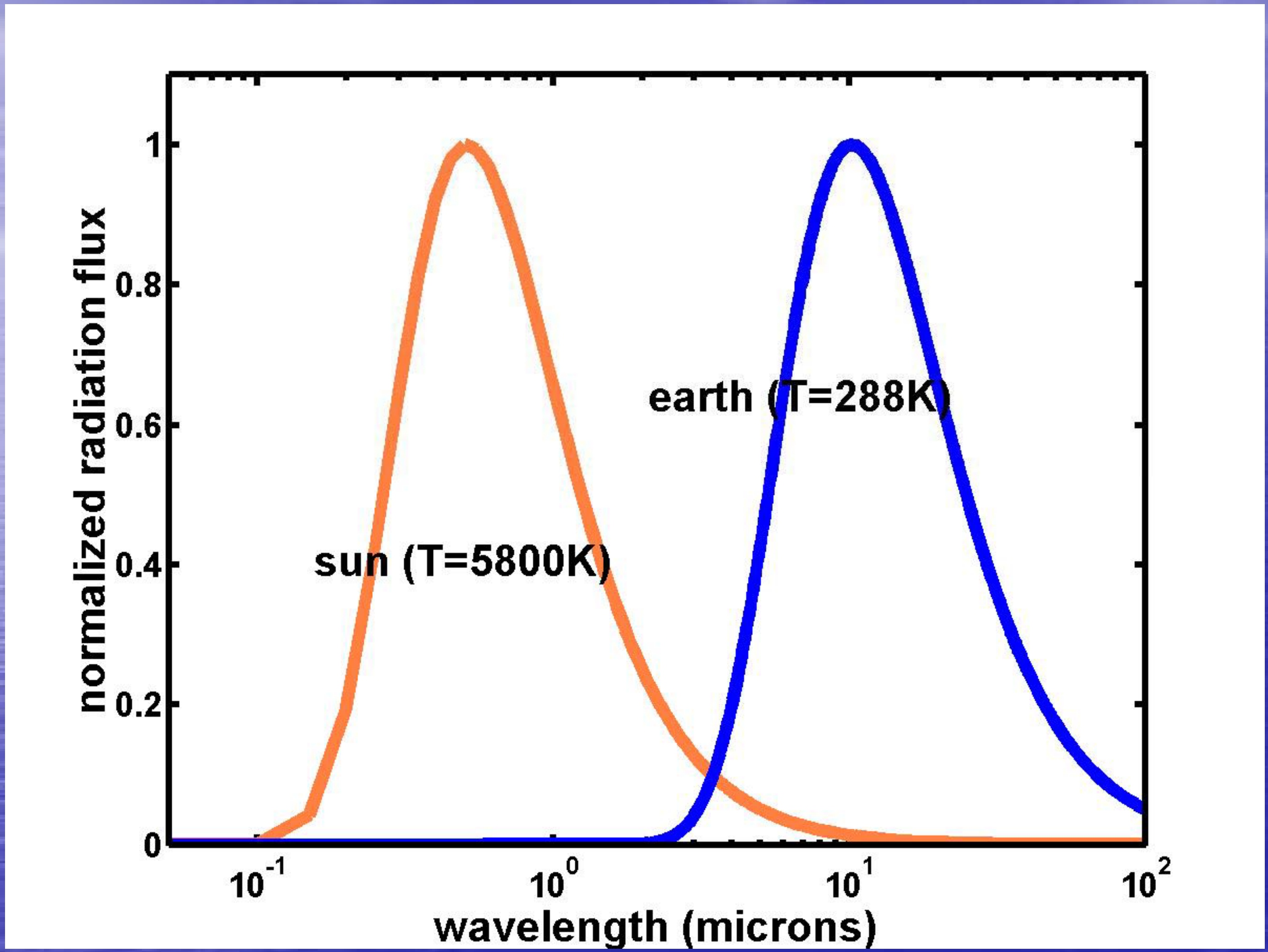

Degeneracy of Second Vibrational Mode of CO2 ©PRB
Bond length = 1.16 A
Bond angle = 180 deg
Bending in x−z plane
Bending in x−y plane
Bending in both planes
z (A)
y (A)
x (A)


Carbon Dioxide ©PRB
Bond length=1.16A angle=180deg
Rotation about the X−axis
Rotation about the Y−axis
Rotation about the Z−axis
z (A)
y (A)
x (A)

UV (.1-.4 μm) Visible (.4-.7 μm) Thermal Infrared (>5 μm)

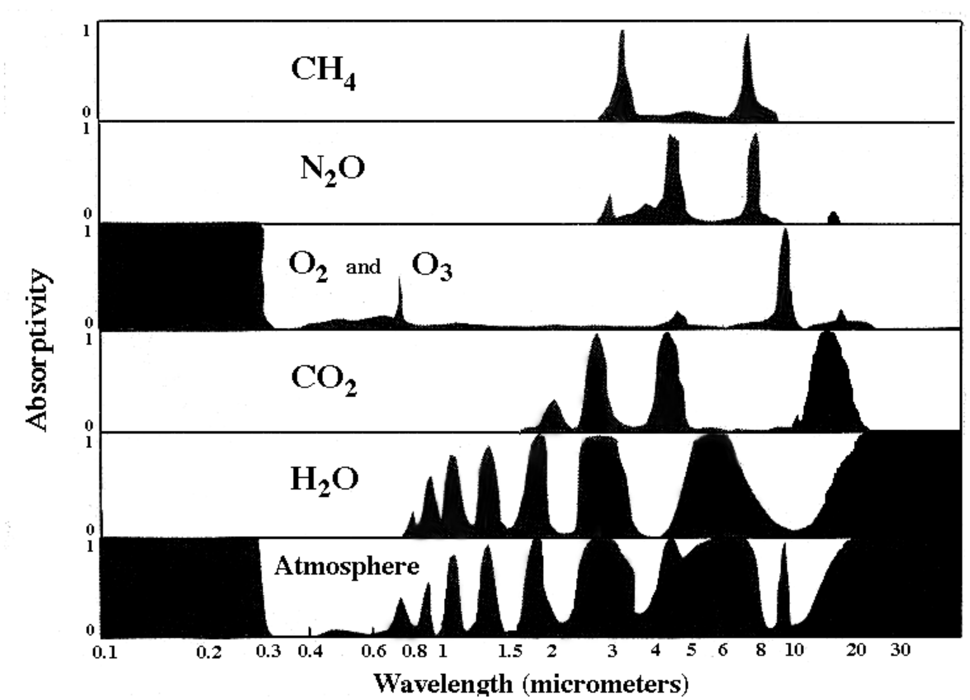
Interaction of the atmosphere with radiation

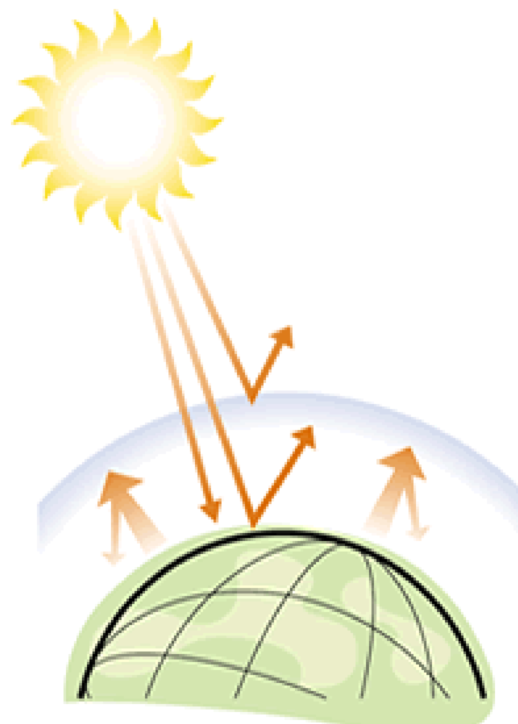




Note that the separation between the solar and terrestrial spectra occurs at about 5 μm

So how does this create a greenhouse effect? The greenhouse effect occurs because **the atmosphere is relatively transparent to the wavelengths of solar radiation, while it absorbs infrared radiation**. So a large chunk of the sun's radiation makes it to the earth's surface. At the same time, the atmosphere containing greenhouse gases absorbs the radiation emitted by the earth's surface, and re-emits it back to the surface, increasing the total energy the surface receives. This forces the earth's surface to become warmer than it would be otherwise.





The greenhouse effect is a naturally-occurring phenomenon on the earth as it is on Venus. The enhancement of this effect by increasing greenhouse gases associated with man-made activities is the reason for concern about climate change.

Greenhouse Gases (part 1)

- Carbon dioxide (CO_2): ~0.4% /yr, fossil fuel combustion, photosynthesis, and ocean, ~380 ppmv, present value

- Water vapor (H_2O): via temperature feedback

- Ozone (O_3): in the troposphere (~10 %)

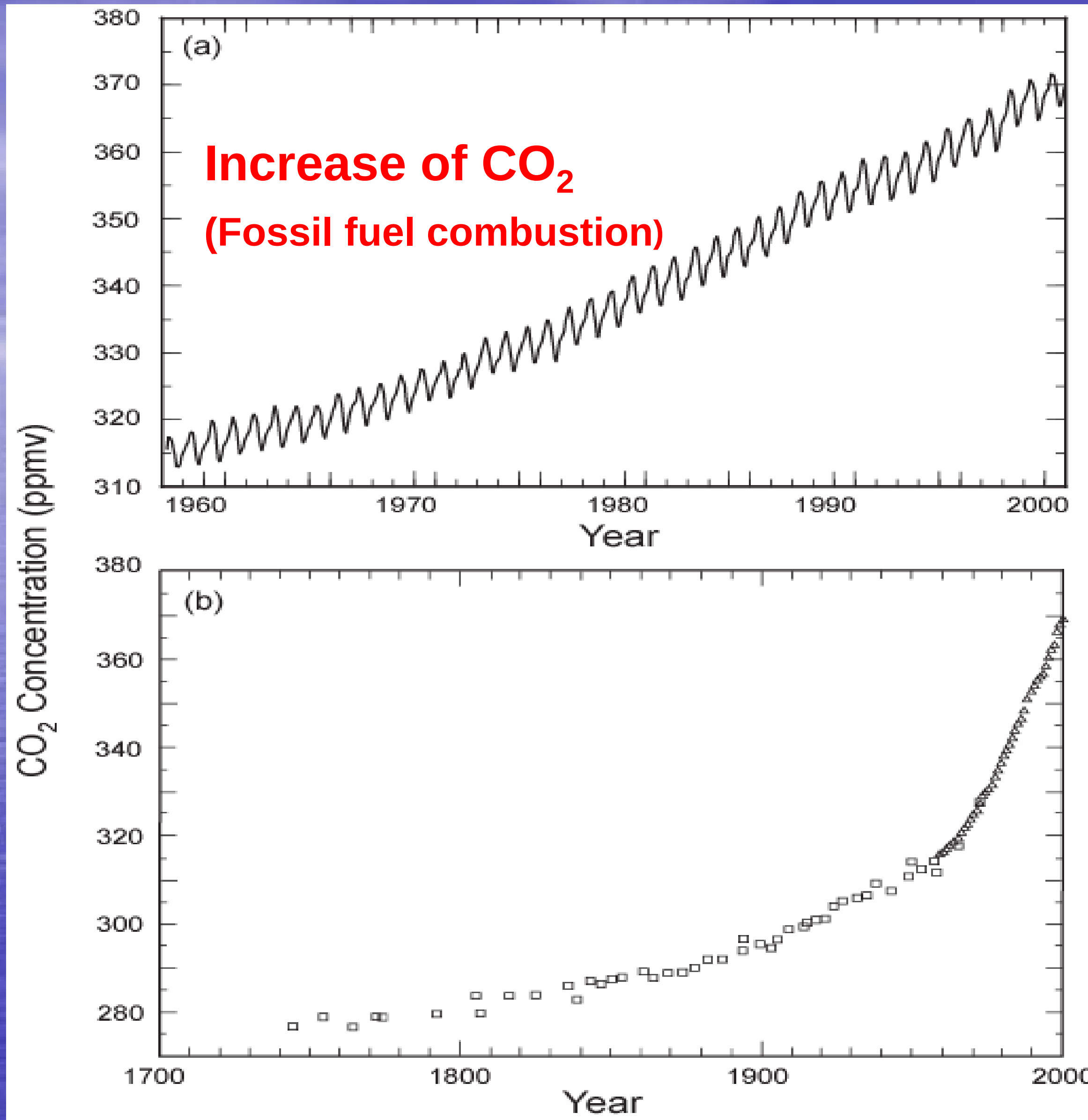
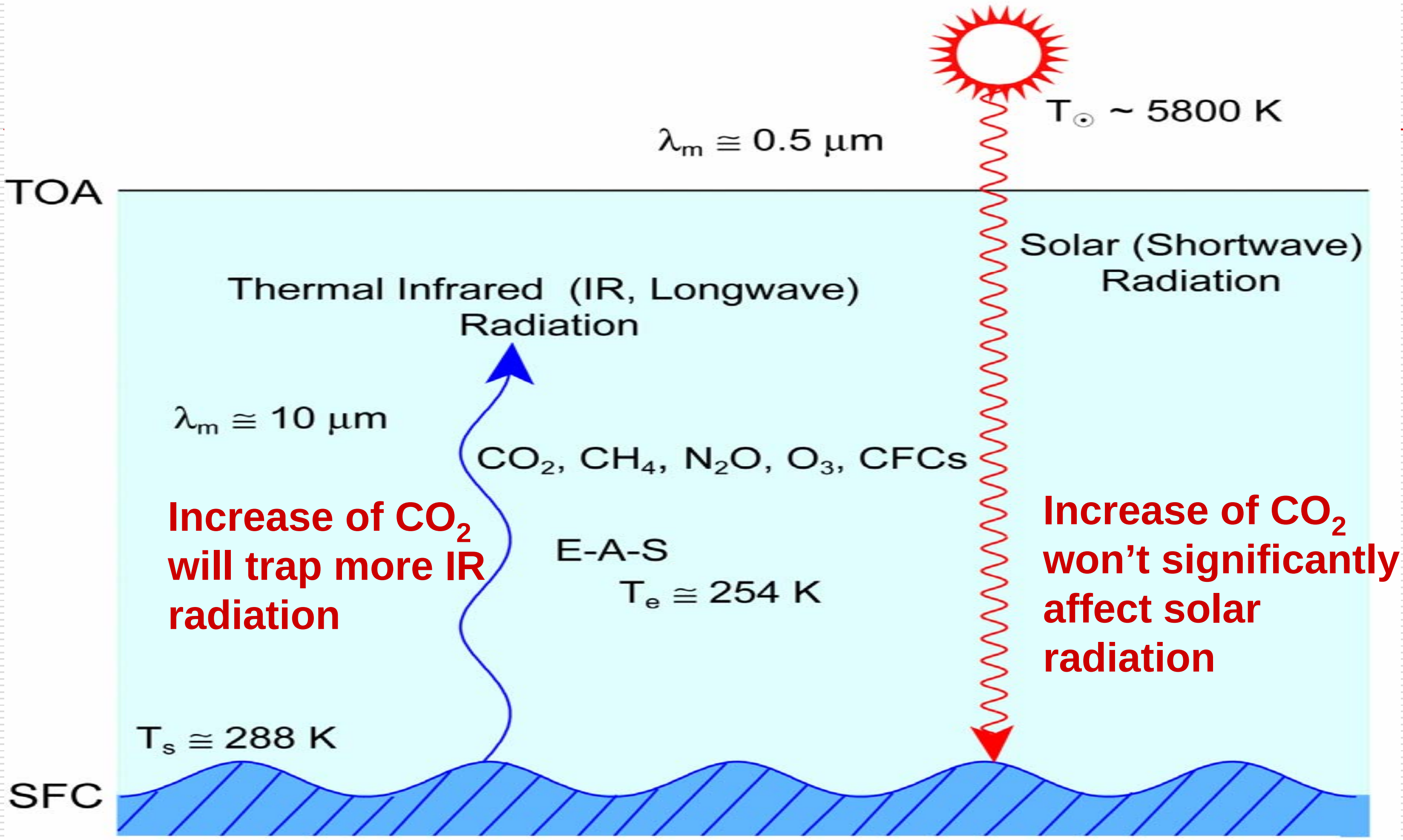


Fig. 8.11 Concentration of atmospheric CO_2 at Mauna Loa Observatory, Hawaii, expressed as a mole fraction in parts per million of dry air for the period 1958-2000 (courtesy of Pieter Tans, Geophysical Monitoring for Climate Change, Environmental Research Laboratory, National Oceanic and Atmospheric Administration). (b) Atmospheric CO_2 concentration for the past 250 years as indicated by measurements in air trapped in ice core from Antarctica determined by Neftel et al. (1985) and extended to the present using the Mauna Loa recorded displayed in (a).

Greenhouse Effect **(Warming)**

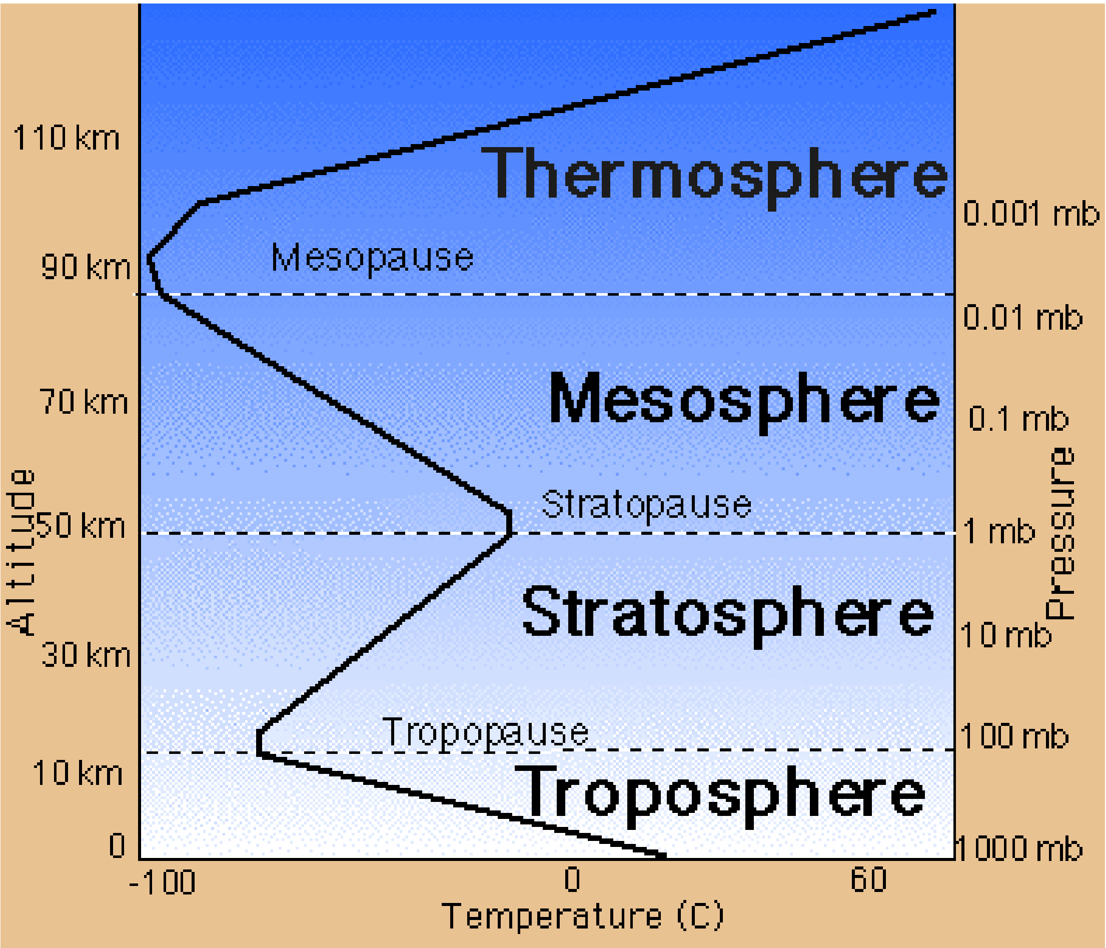


$T_s = T_e + \gamma H$

γ = Lapse rate $\cong$ 6.5 K/km

H = Effective emission height $\cong$ 5 km

Thermal structure of the atmosphere

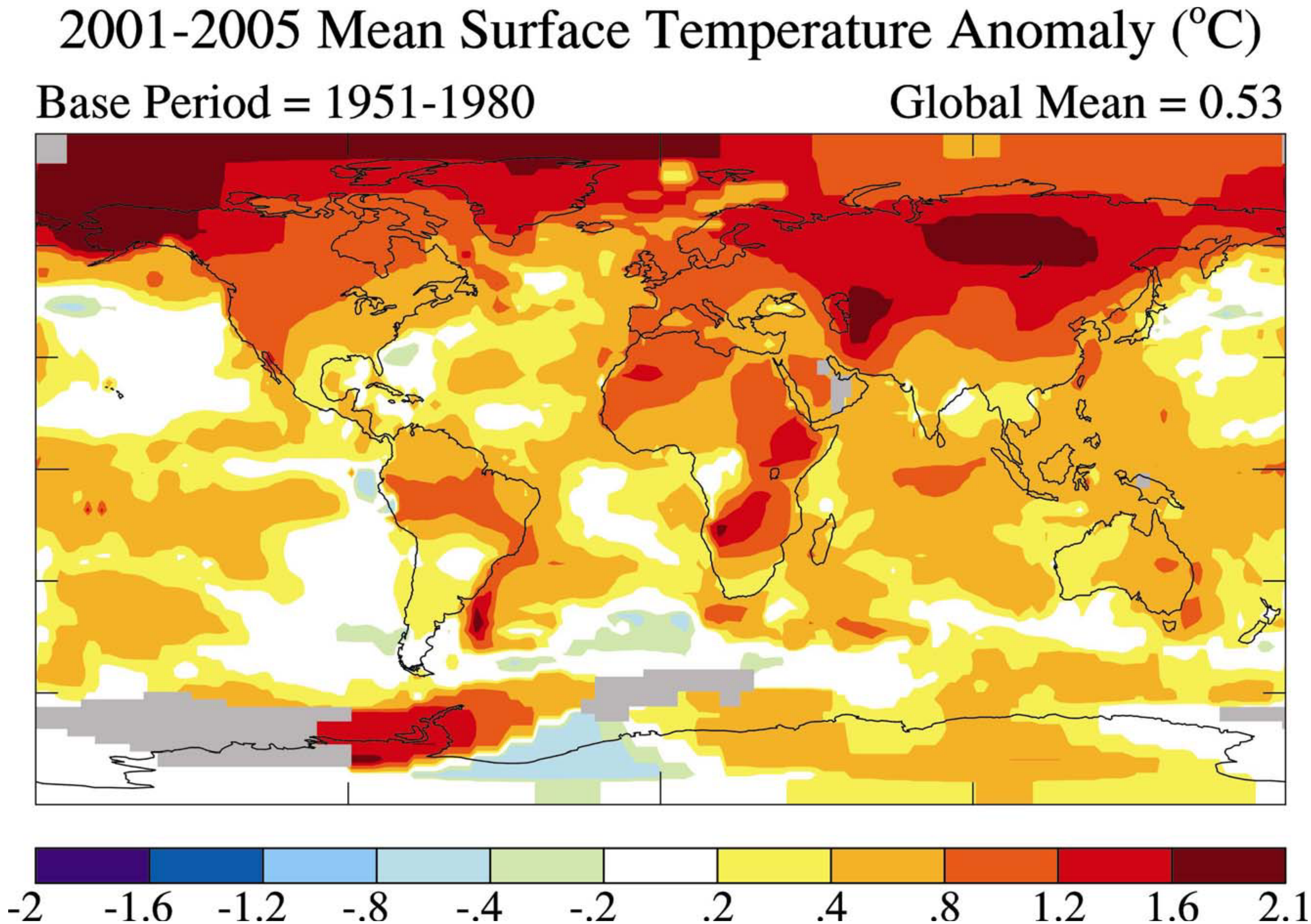


Increase in Greenhouse Gases

Colder

Warmer

90% of the atmosphere's mass is in the troposphere.



(After James E. Hansen 2006)

Radiative Equilibrium (for extra credit)

Energy Conservation Principle at the top of the atmosphere (TOA)

Incoming solar energy absorbed = Outgoing infrared energy emitted

$$S(1-r)\times\pi a_e^2 = \sigma T_e^4 \times 4\pi a_e^2$$

where

σ = Stefan-Boltzmann constant

S = Solar constant (total solar energy/time/area at TOA)

r = Global albedo ≅ 0.3

a_e = Radius of the Earth

T_e = Equilibrium temperature of the Earth-atmosphere-system

thus

$$T_e = \left[S(1-r)/4\sigma\right]^{1/4}$$