41st Saas-Fee Course
From Planets to Life
3-9 April 2011

Lecture 1: Fundamentals of Planetary Climates

Blackbody Radiation/
Planetary Energy Balance/
The Greenhouse Effect/
Global Warming

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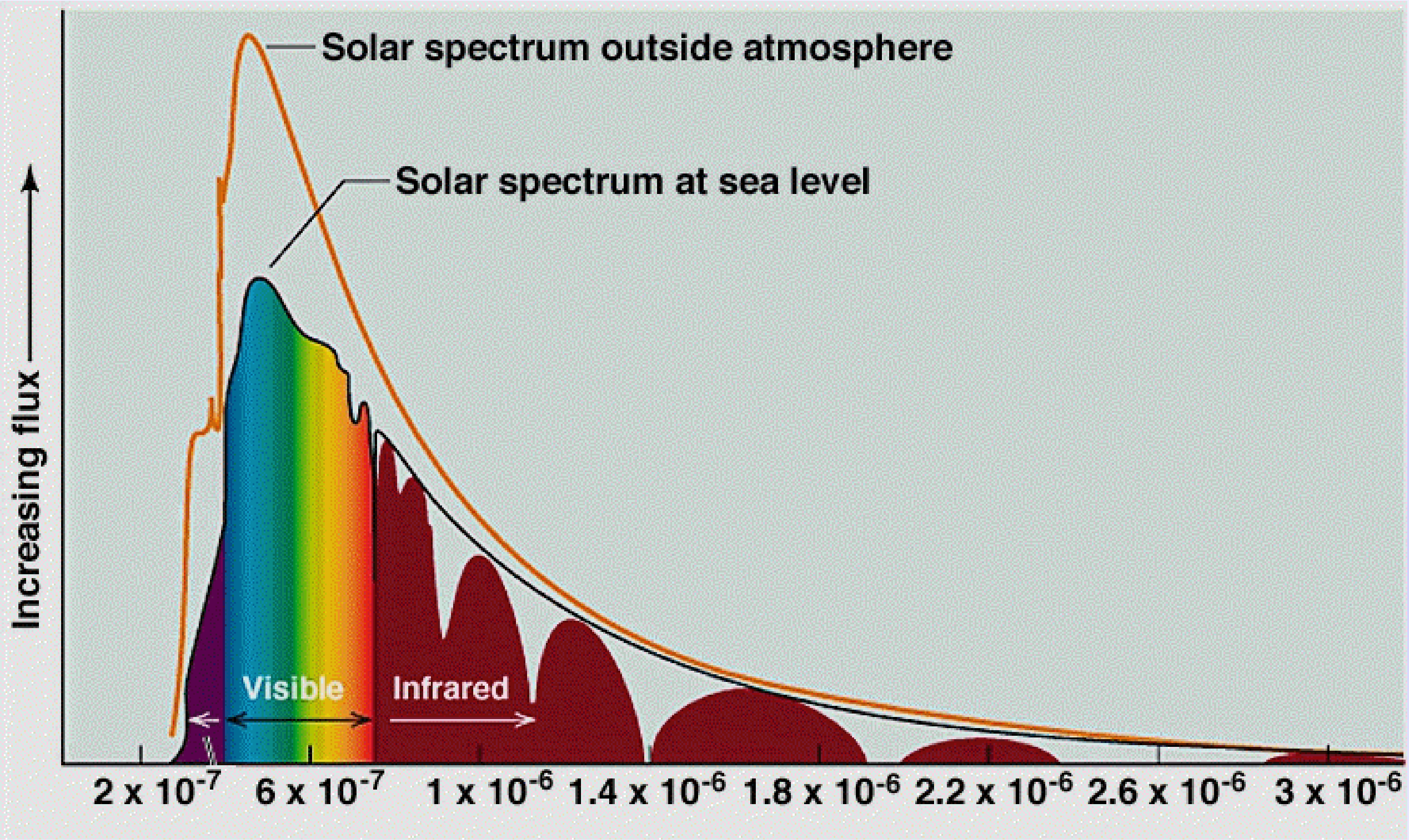
Solar Spectrum

The sun emits radiation at all wavelengths

Most of its energy is in the
IR-VIS-UV
portions of the spectrum

~50% of the energy is in the **visible** region
~40% in the **near-IR**
~10% in the **UV**



Wavelength (m)

Blackbody Radiation

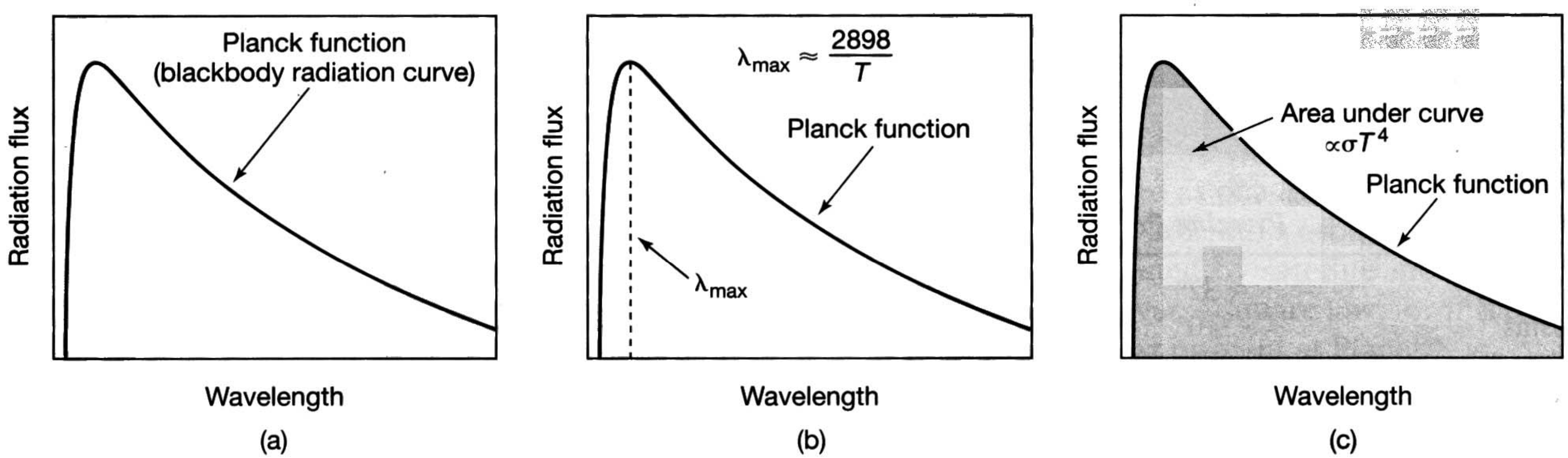


FIGURE 3-7

(a) The Planck function, or blackbody radiation curve; (b) Wien's law; (c) the Stefan–Boltzmann law.

Planck function

$$B_\lambda(T) = \frac{2hc^2\lambda^{-5}}{(e^{hc/k\lambda T} - 1)}$$

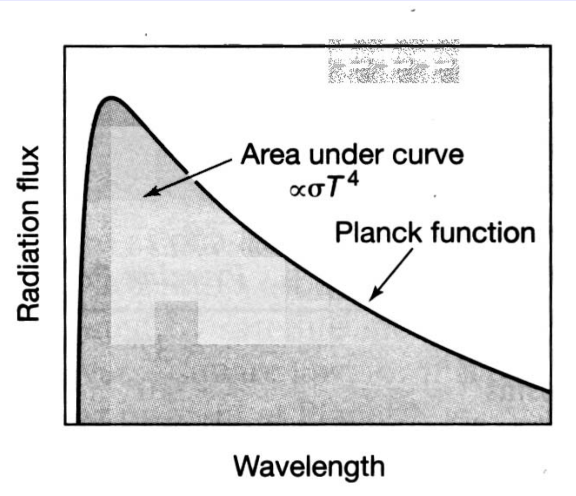
Blackbody radiation—radiation emitted by a body that emits (or absorbs) equally well at all wavelengths

Basic Laws of Radiation

1) All objects emit radiant energy.

2) Hotter objects emit more energy than colder objects. The amount of energy radiated is proportional to the temperature of the object raised to the fourth power.

➡ This is the Stefan-Boltzmann Law



$$F = \sigma T^4$$

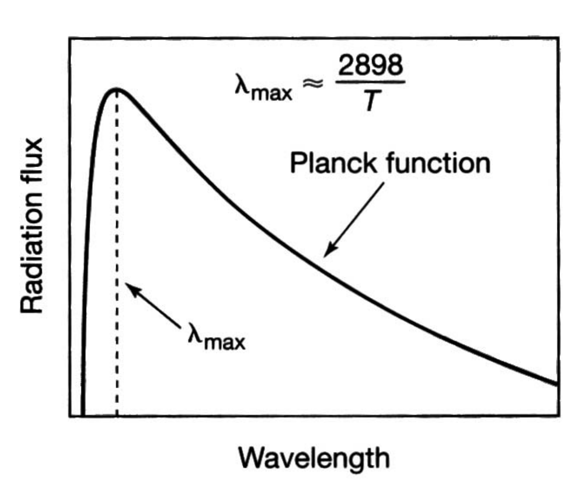
F = flux of energy (W/m^2)
T = temperature (K)
$\sigma = 5.67 \times 10^{-8}\ W/m^2K^4$ (a constant)

Basic Laws of Radiation

1) All objects emit radiant energy.

2) Hotter objects emit more energy than colder objects (per unit area). The amount of energy radiated is proportional to the temperature of the object.

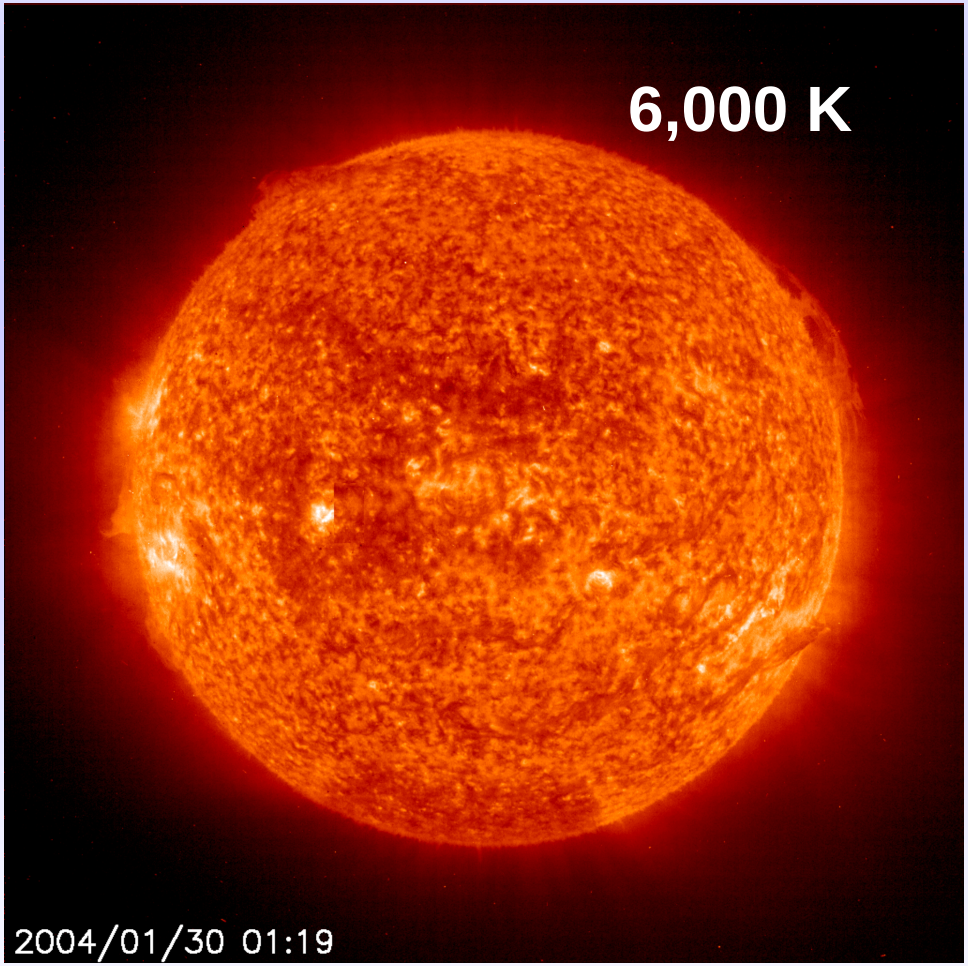
3) The hotter the object, the shorter the wavelength (λ) of the peak in emitted energy.

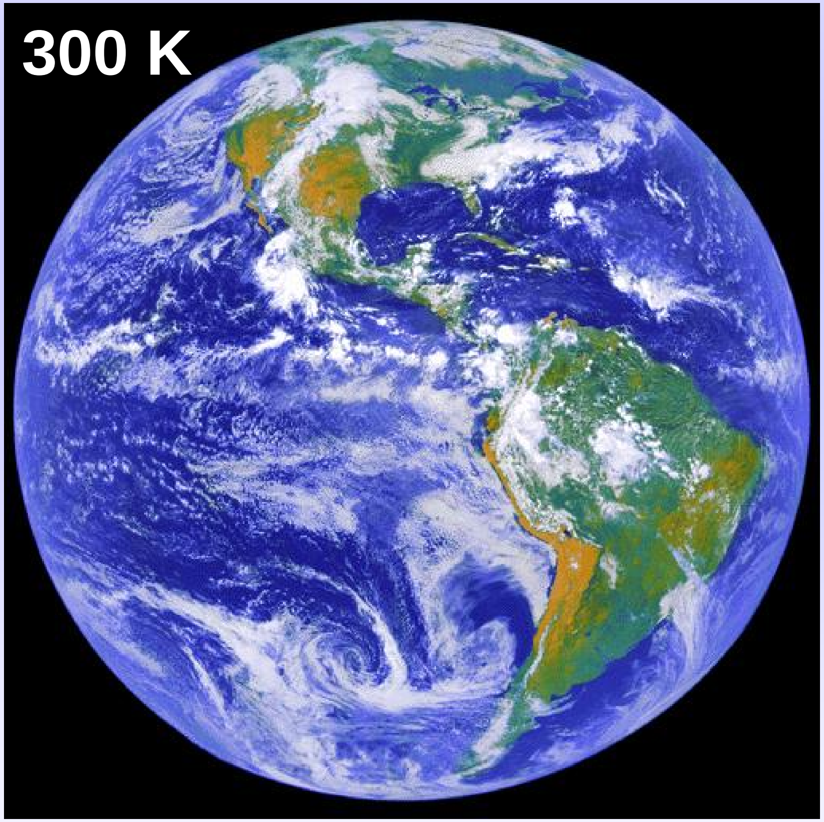


➡This is Wien's Law:

$$\lambda_{\max} = \frac{2898(\mu m \cdot K)}{T}.$$

We can use these equations to calculate properties of energy radiating from the Sun and the Earth.

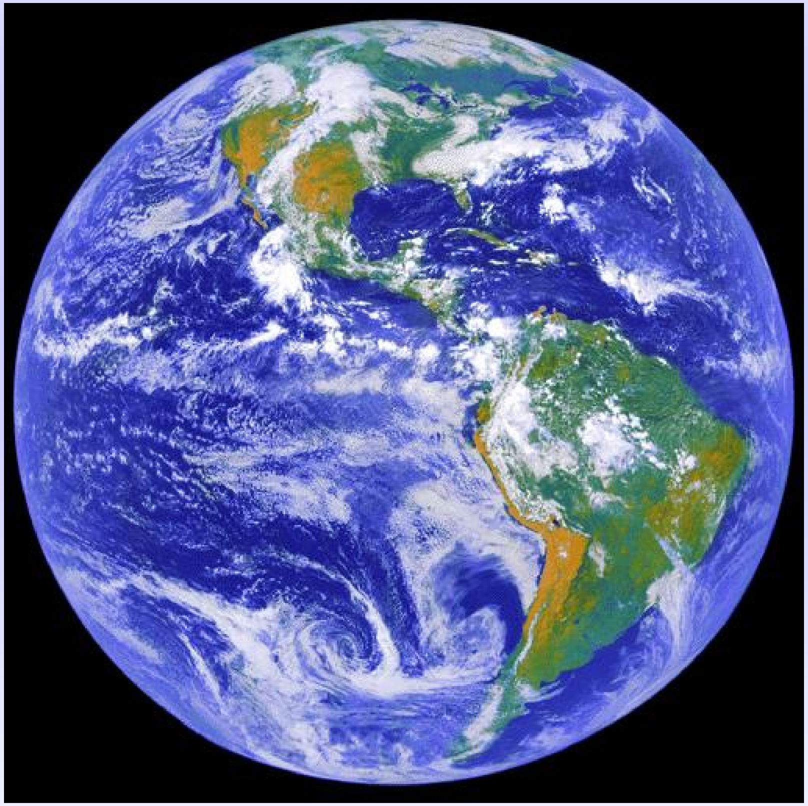




	T (K)	λ_{max} (μm)	region in spectrum	F (W/m^2)
Sun	6000	0.5	Visible (green)	7×10^7
Earth	300	10	infrared	460

Planetary Energy Balance

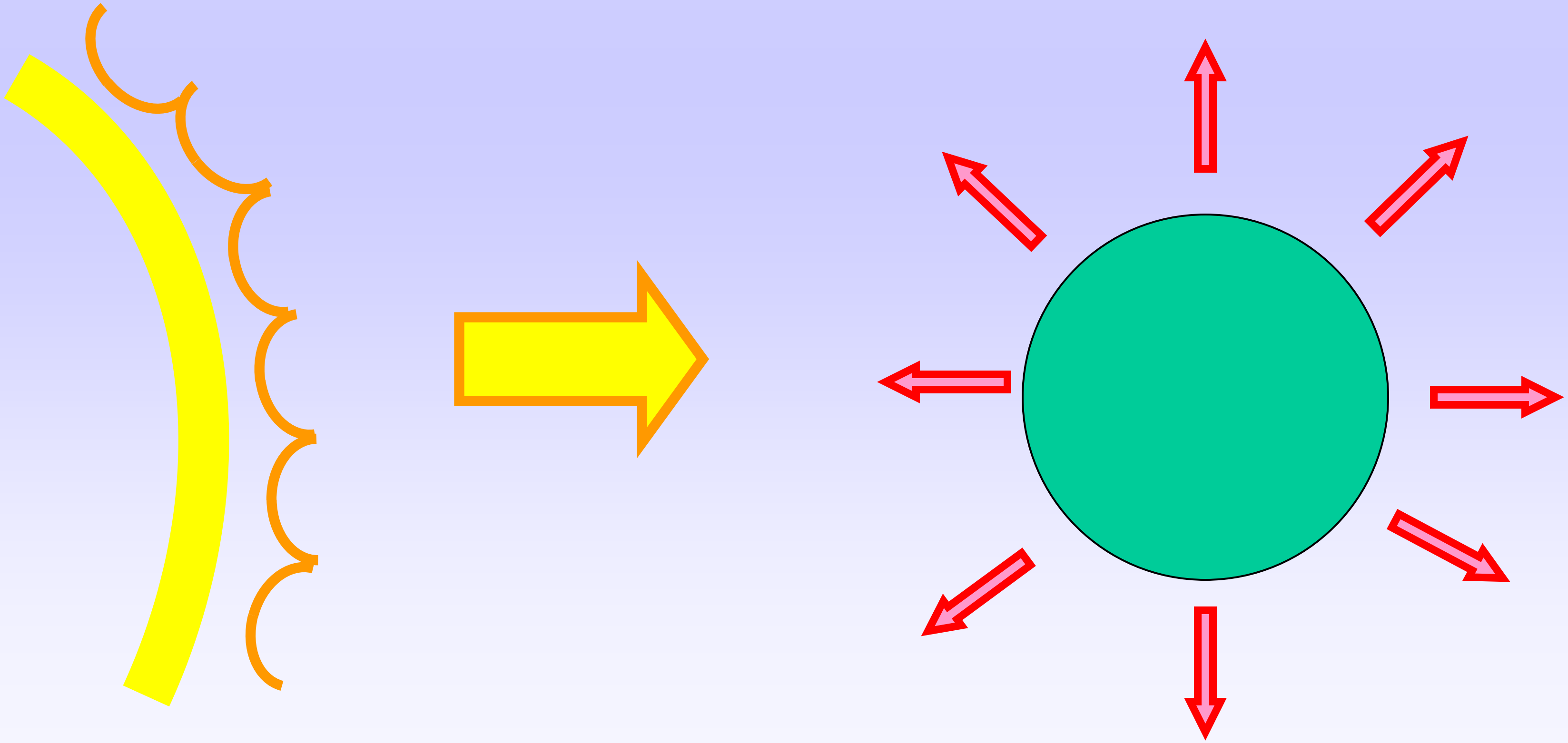
- We can use the concepts learned so far to calculate the radiation balance of the Earth



Energy Balance:

The amount of energy delivered to the Earth is equal to the energy lost from the Earth.

Otherwise, the Earth's temperature would continually rise (or fall).



How much energy does the Earth emit?

$$E_{out} = F \times (\text{area of the Earth})$$

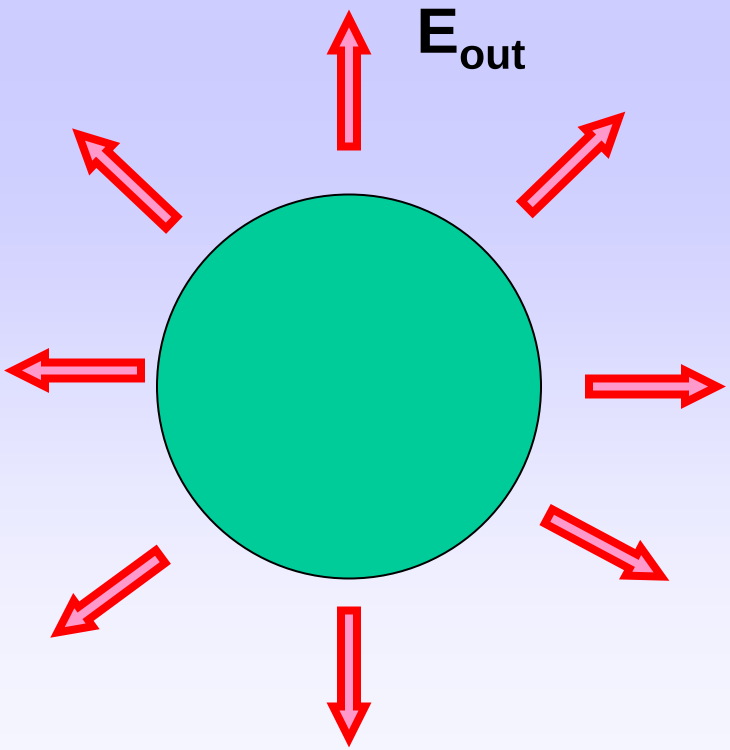
$F = \sigma\, T_e^4$

$\text{Area} = 4\, \pi\, r_e^2$

$$\mathbf{E_{out} = (\sigma\, T_e^4) \times (4\, \pi\, r_e^2)}$$

$T_e \equiv$ effective radiating temperature

(We are treating the Earth like a blackbody)

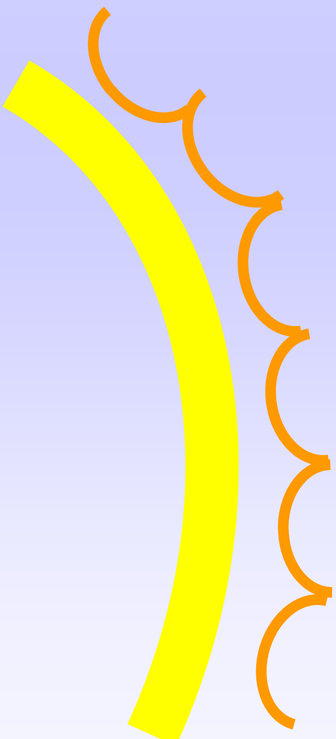


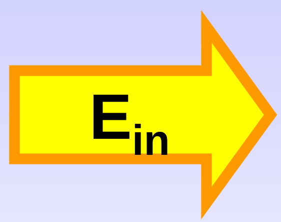
How much solar energy reaches the Earth?

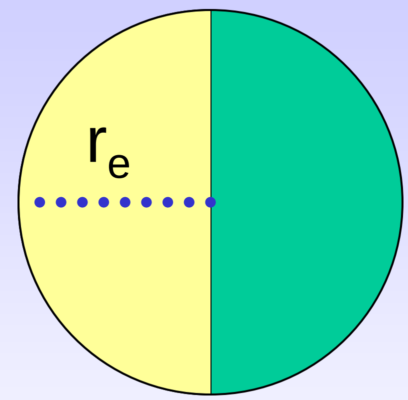
We can assume solar radiation covers the area of a circle defined by the radius of the Earth (r_e).

$$E_{in} = S_o \text{ x (area of circle)}$$

$$\mathbf{E_{in} = S_o\ (W/m^2) \text{ x } \pi\, r_e^2\ (m^2)}$$



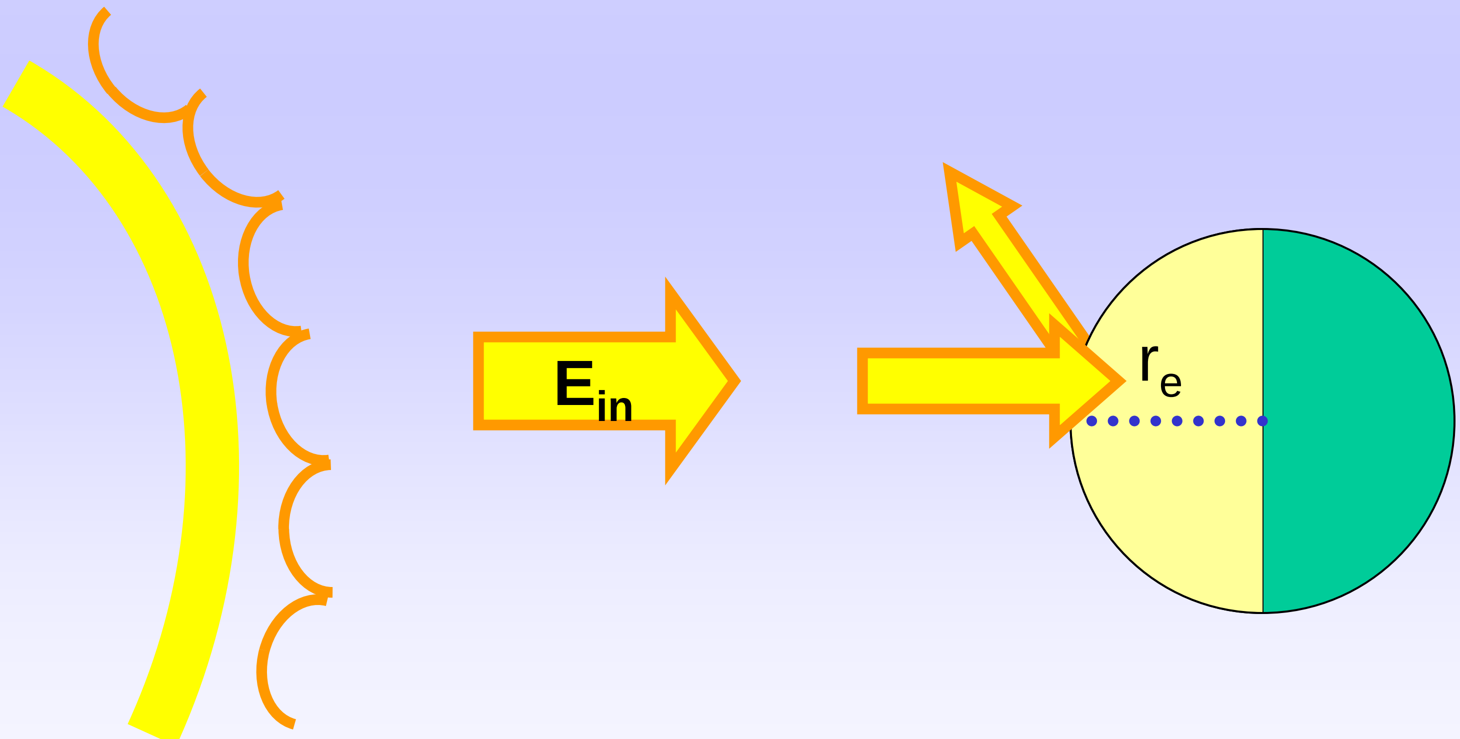




How much solar energy reaches the Earth?

Albedo (A) = % energy reflected away

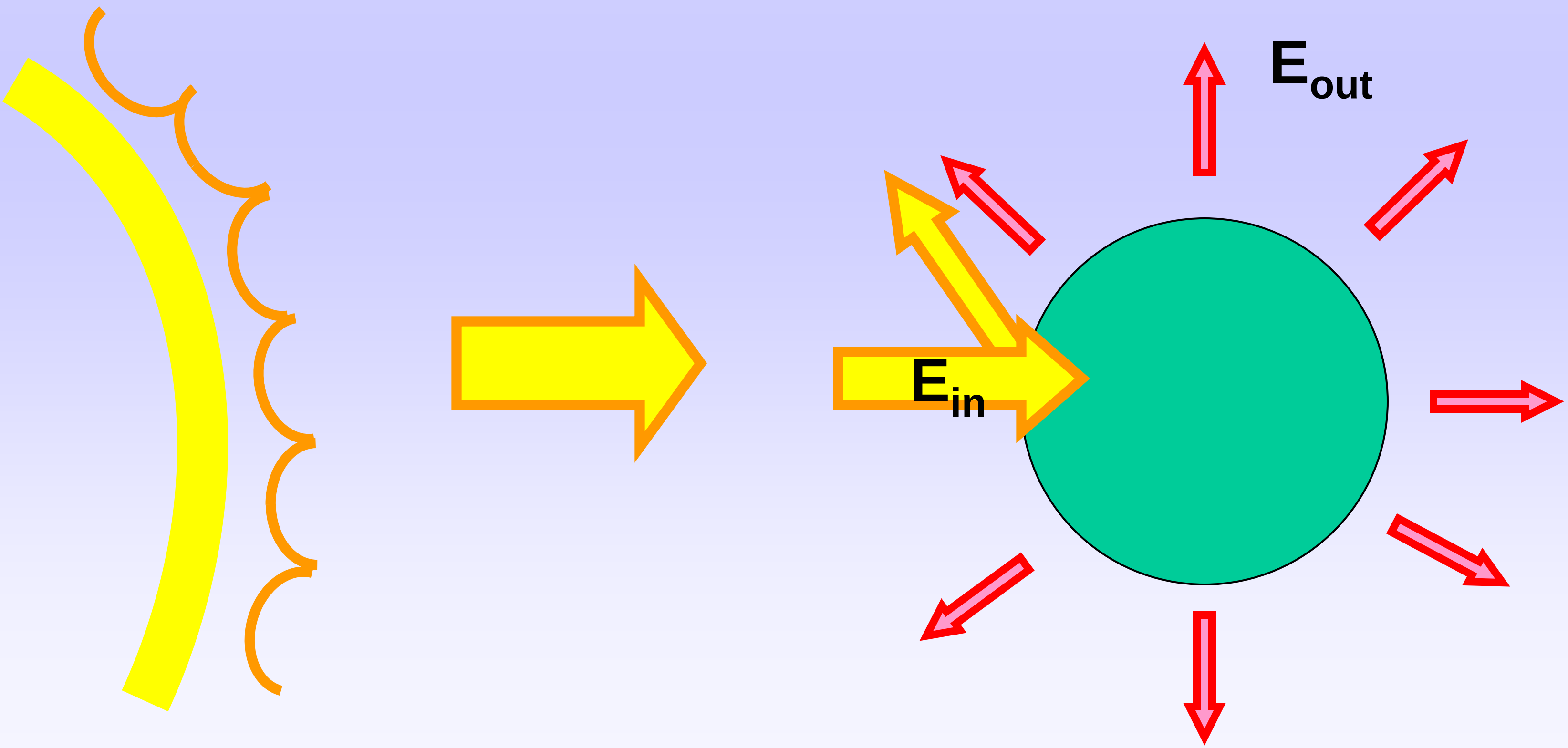
$$E_{in} = S_o \pi r_e^2 (1-A)$$



Energy Balance:

$$E_{in} = E_{out}$$

$$S_o\ \pi\ r_e^2\ (1\text{-}A) = \sigma\ T_e^4\ (4\ \pi\ r_e^2)$$

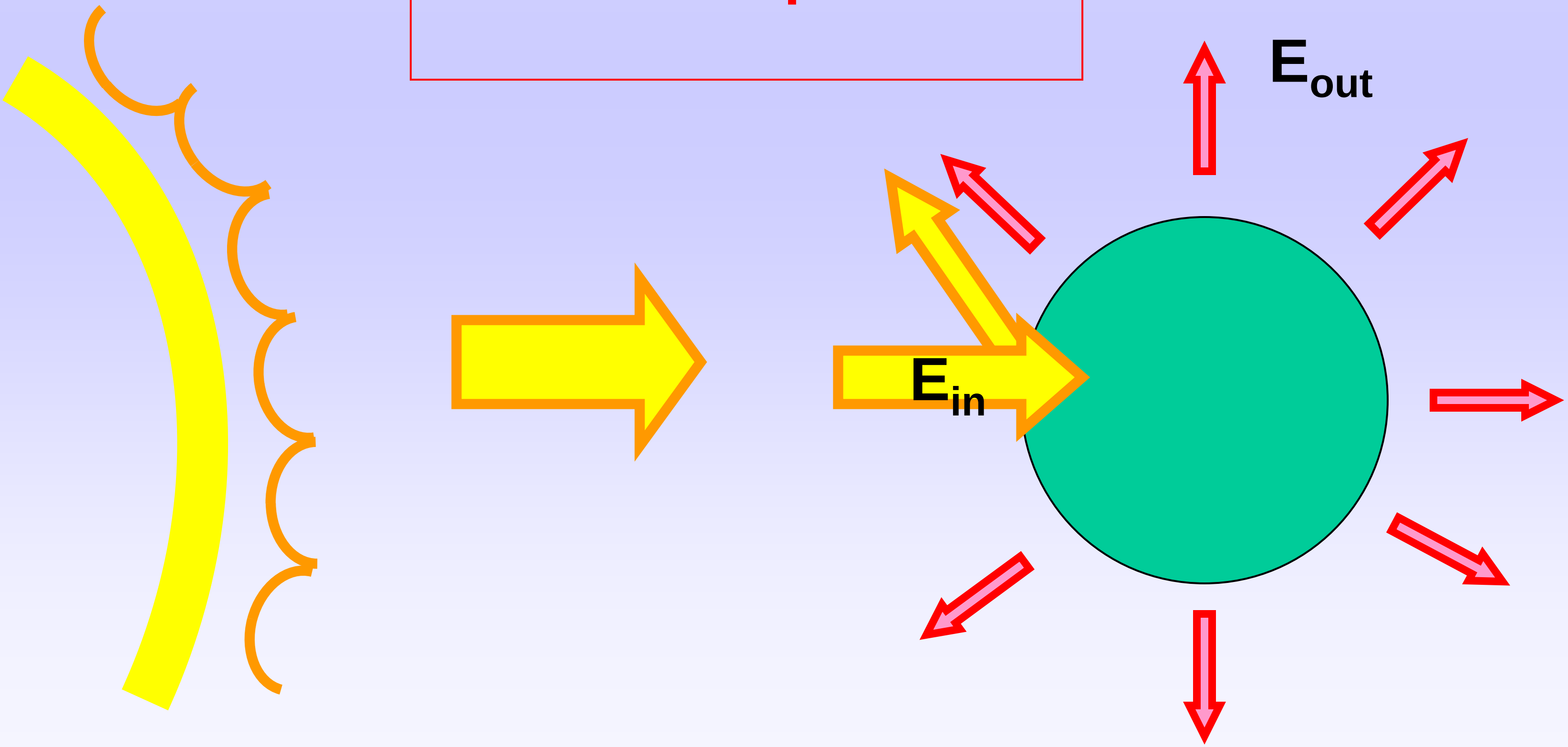


Energy Balance:

$$E_{in} = E_{out}$$

$$S_o\,(1-A) = \sigma\, T_e^4\,(4)$$

$$\boxed{\sigma T_e^4 = \frac{S_o(1-A)}{4}}$$



$$\mathbf{T_e^4 = \frac{S_o(1-A)}{4\sigma}}$$

For Earth:

S_o = 1370 W/m^2

A = 0.3

σ = 5.67 x 10^{-8} W/m^2/K^4

$$\mathbf{T_e^4 = \frac{(1370\ W/m^2)(1-0.3)}{4\ (5.67 \times 10^{-8}\ W/m^2/K^4)}}$$

so

T_e = 255 K **(= -18^{o}C, or 0^{o}F)**

Is the Earth's surface really -18 ^{o}C?

NO. The actual temperature is warmer!

The observed surface temperature (T_s) is 15 ^{o}C, or about 59 ^{o}F.

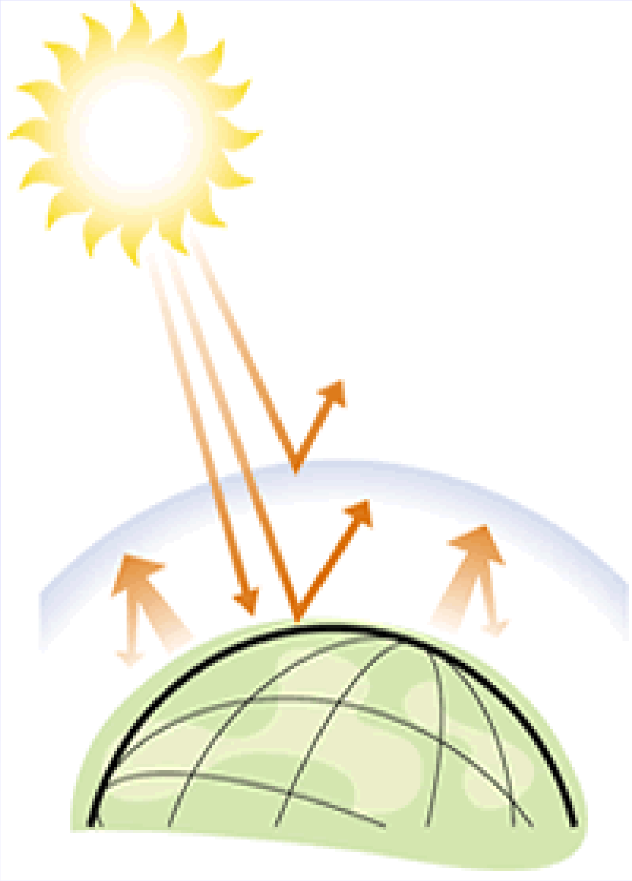
The difference between observed and effective temperatures (ΔT):

$$\Delta T = T_s - T_e$$

$$\Delta T = 15^{o}C - (-18^{o}C)$$

$$\boldsymbol{\Delta T = +33\ ^{o}C}$$

The greenhouse effect



- **ΔT = + 33 oC**
- In other words, the Earth is 33^{o}C <u>warmer</u> than expected based on blackbody calculations and the known input of solar energy.
- This extra warmth is what we call the GREENHOUSE EFFECT.
- It is a result of warming of the Earth's surface by the absorption and reemission of radiation by molecules in the atmosphere

Composition of the Atmosphere

Air is composed of a mixture of gases:

Gas	concentration (%)	ppm
N_2	78	
O_2	21	
Ar	0.9	
H_2O	variable	
CO_2	0.039	390 ppm
CH_4		1.7
N_2O		0.3
O_3		1.0 to 0.01

(stratosphere-surface)

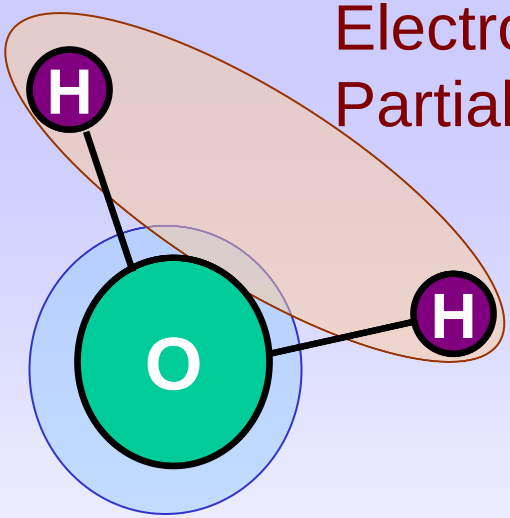
greenhouse gases

What makes a greenhouse gas absorb infrared radiation?

- Molecules with an *electric dipole moment* (either permanent or induced) can absorb and emit IR radiation

Water

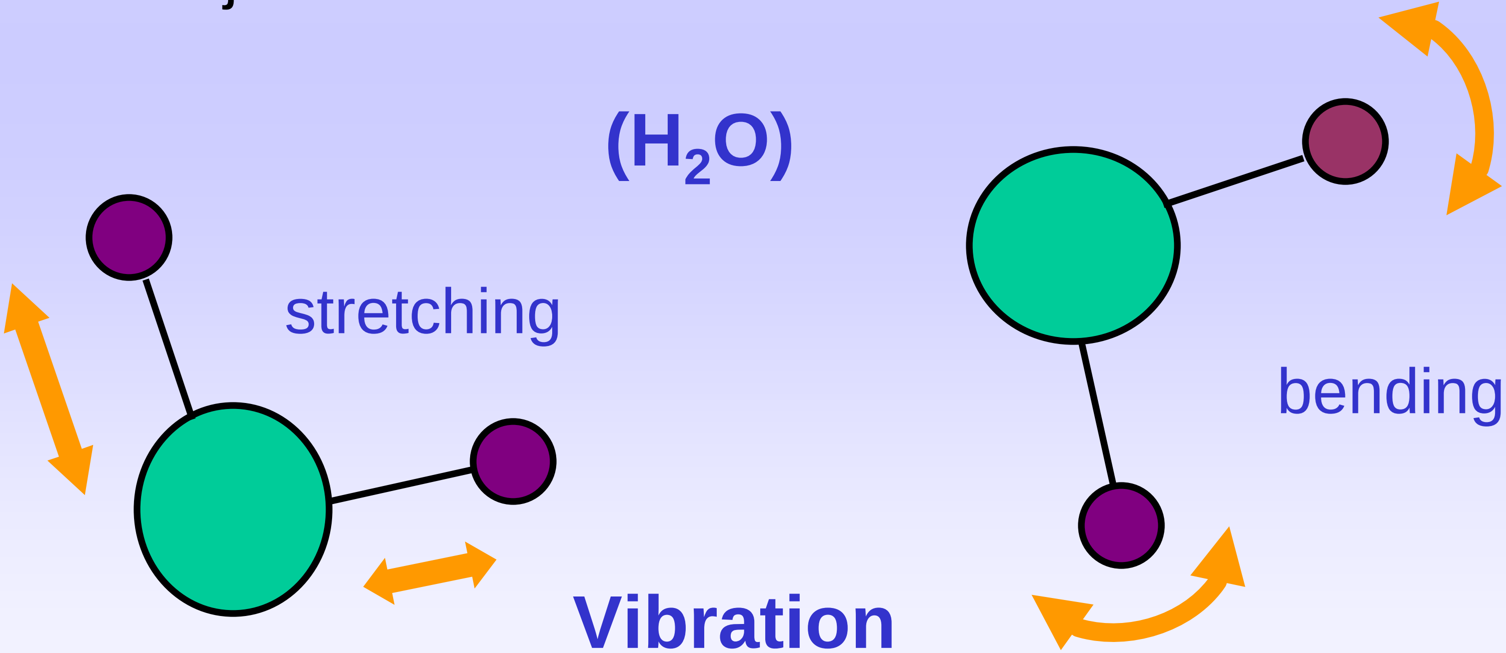
Electron-poor region:
Partial positive charge



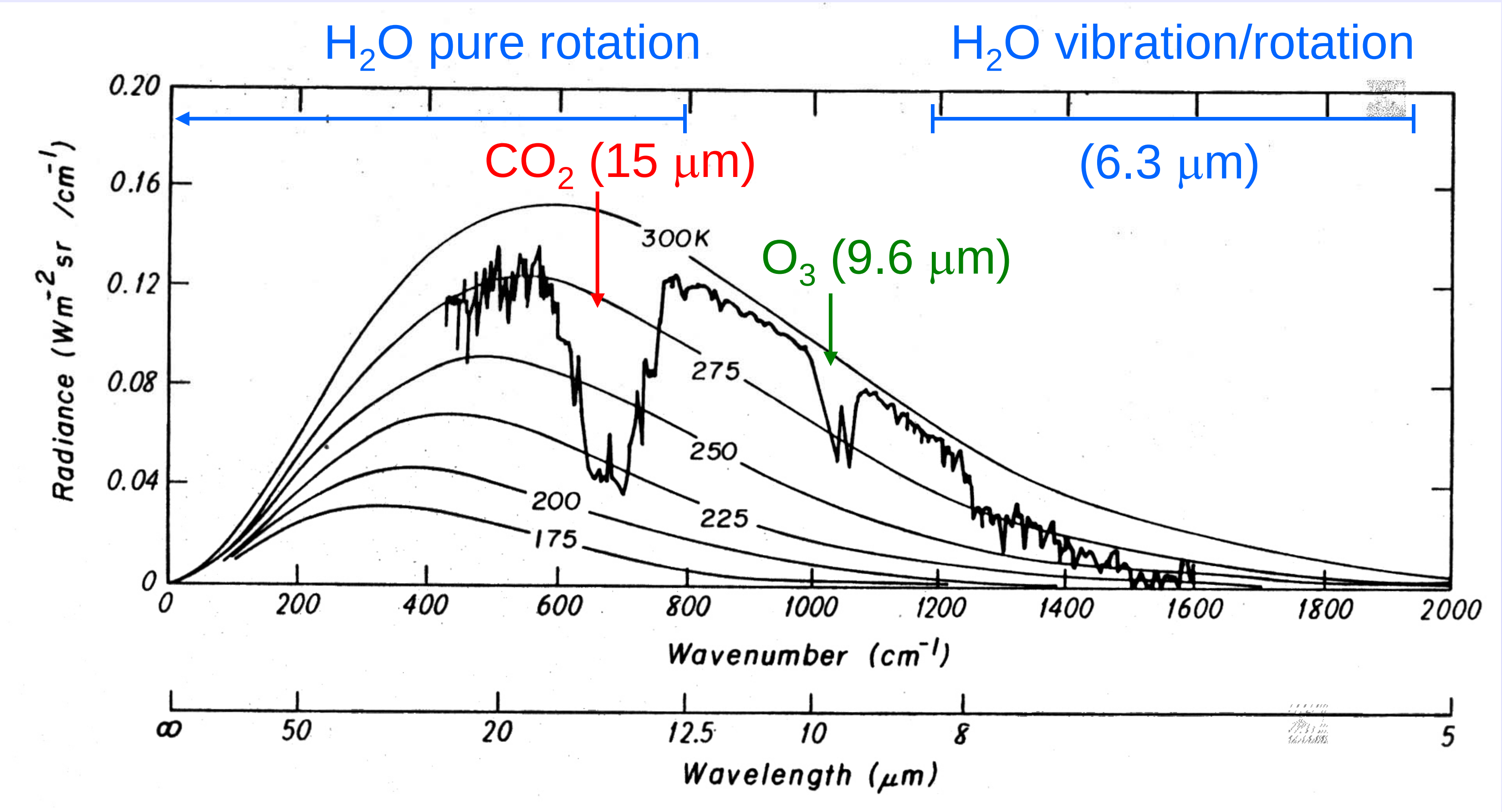
Electron-rich region:
Partial negative charge

oxygen is more electronegative than hydrogen

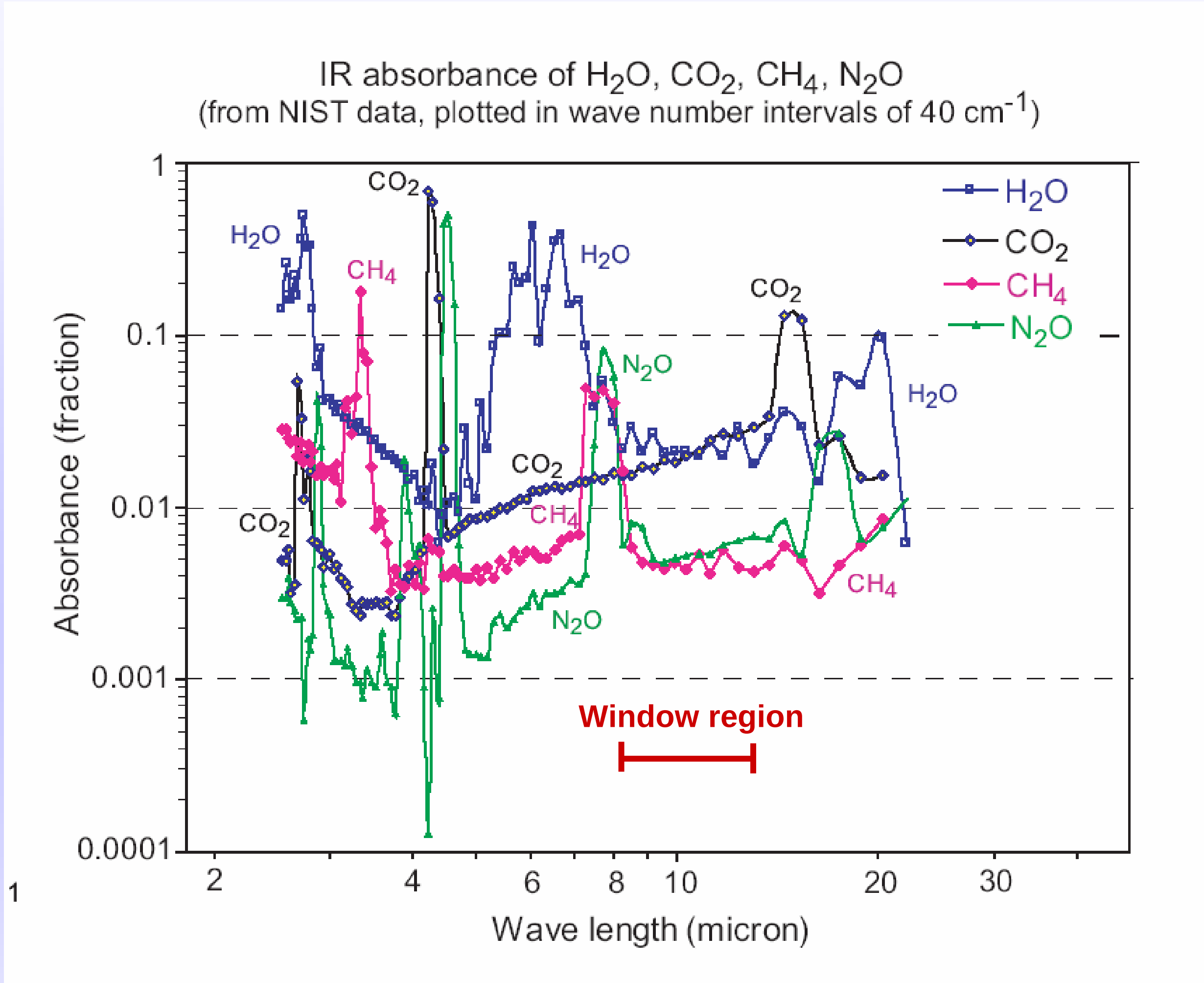
- H_2O and CO_2 can both **rotate** and **vibrate**
- The *pure rotation band* of H_2O occurs longward of ~12 μm and is important for climate, as is the 6.3-μm vibration band
- The *15-μm bending mode* vibration of CO_2 plays a major role in Earth's climate



Thermal-IR spectrum for Earth



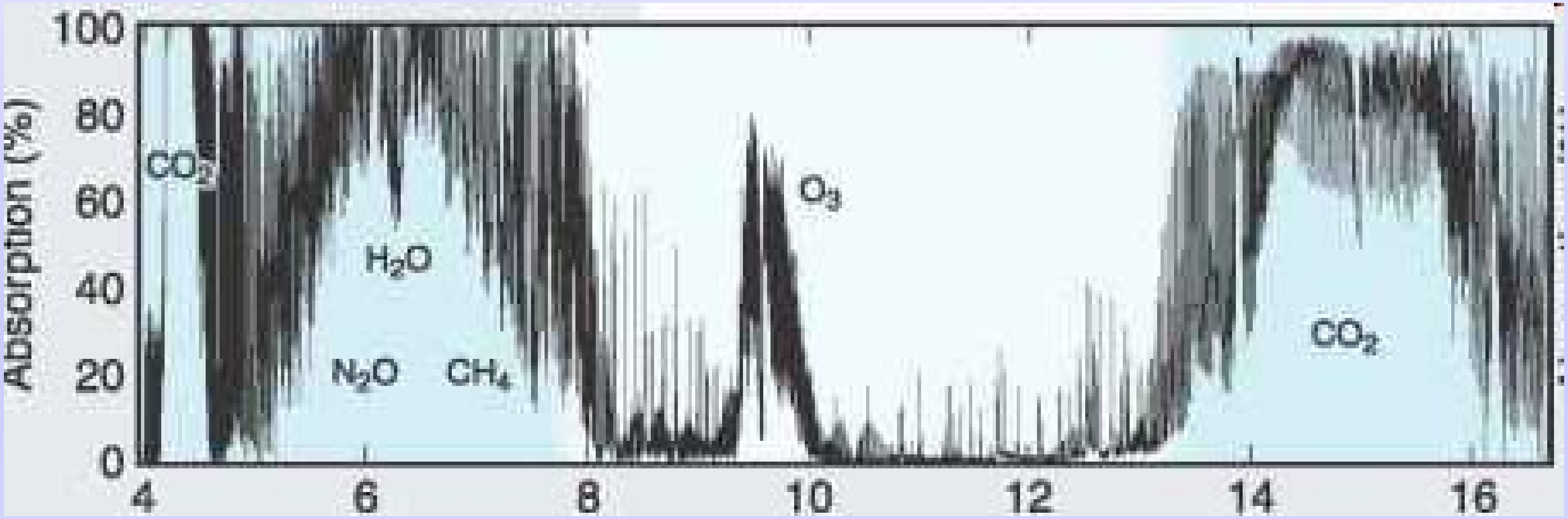
Ref.: K.-N. Liou, *Radiation and Cloud Physics Processes in the Atmosphere* (1992)



- CH_4 and N_2O are good greenhouse gases because they absorb in the 8-12 μm "window" region where H_2O and CO_2 absorption is weak
- But CH_4 is actually *not* as good a greenhouse gas as CO_2 when one compares them at equal concentrations

Figure courtesy of Abe Lerman, Northwestern Univ.

Higher resolution spectra

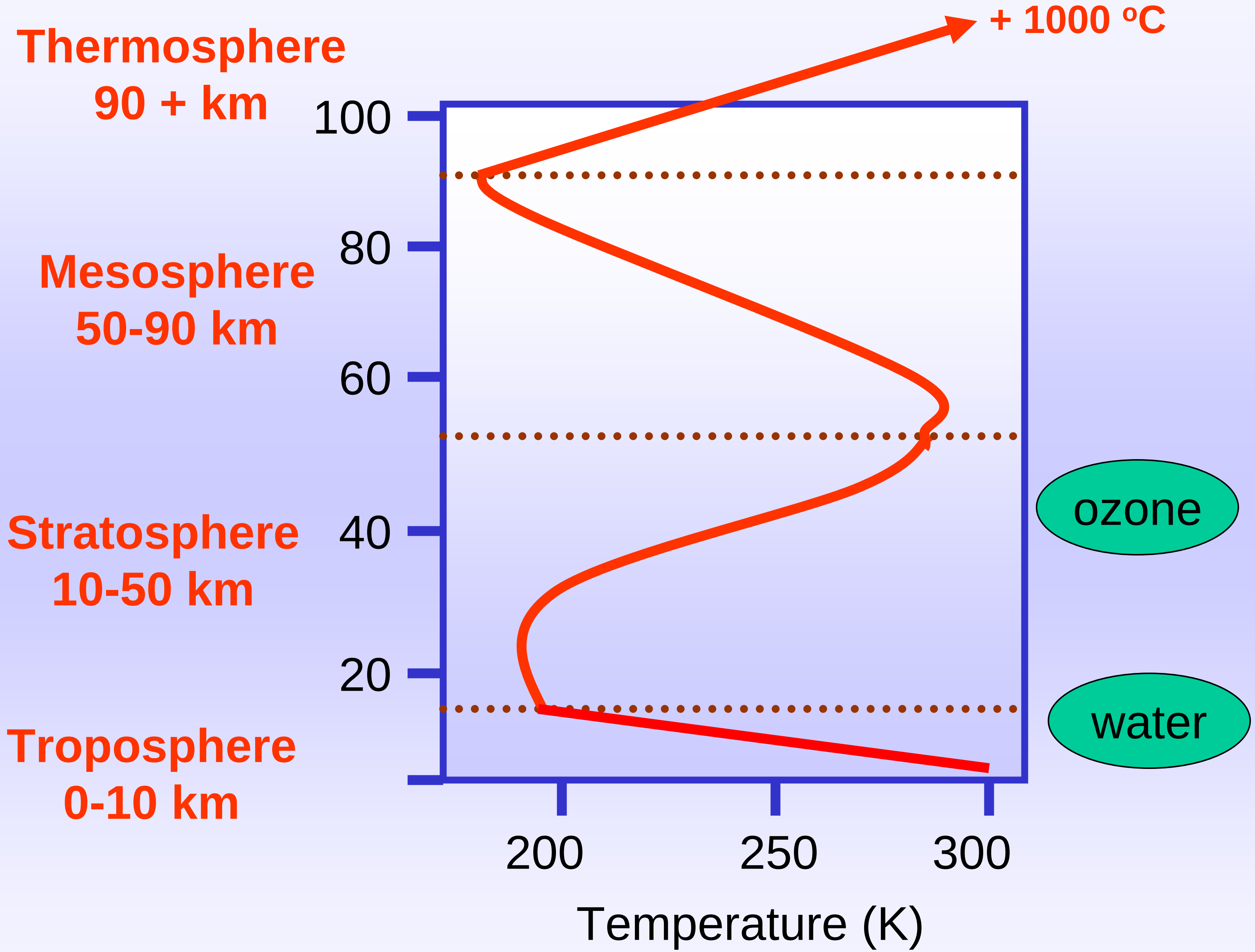


- The actual infrared absorption spectra of molecules are extremely complex
- Parameterizing the absorption by the various greenhouse gases in a time-efficient manner is one of the greatest challenges of climate modeling

Uncertain effects of clouds

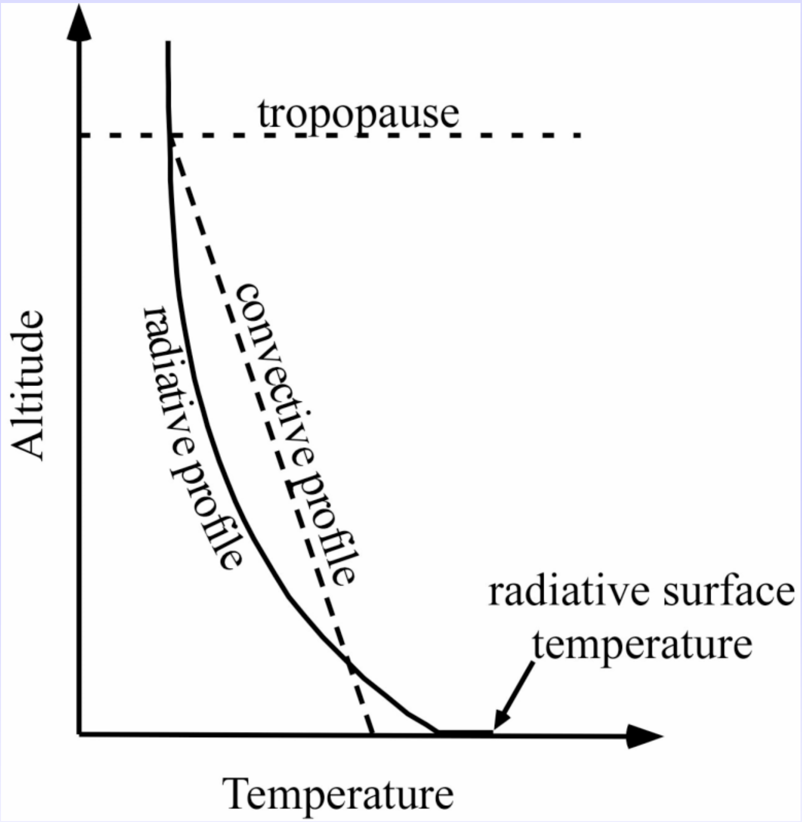
- Even if we do a good job on gaseous absorption, radiative transfer in planetary atmospheres is still highly uncertain because of the effects of *clouds*
  - High clouds (cirrus) warm the surface
  - Low clouds (cumulus and stratus) cool it
  - How will clouds change as the climate changes?

- Putting these gases into Earth's atmosphere results in a vertical temperature profile that looks like this $\Rightarrow$


Thermosphere
90 + km
Mesosphere
50-90 km
Stratosphere
10-50 km
Troposphere
0-10 km
+ 1000 ºC
100
80
60
40
20
200
250
300
Temperature (K)
ozone
water

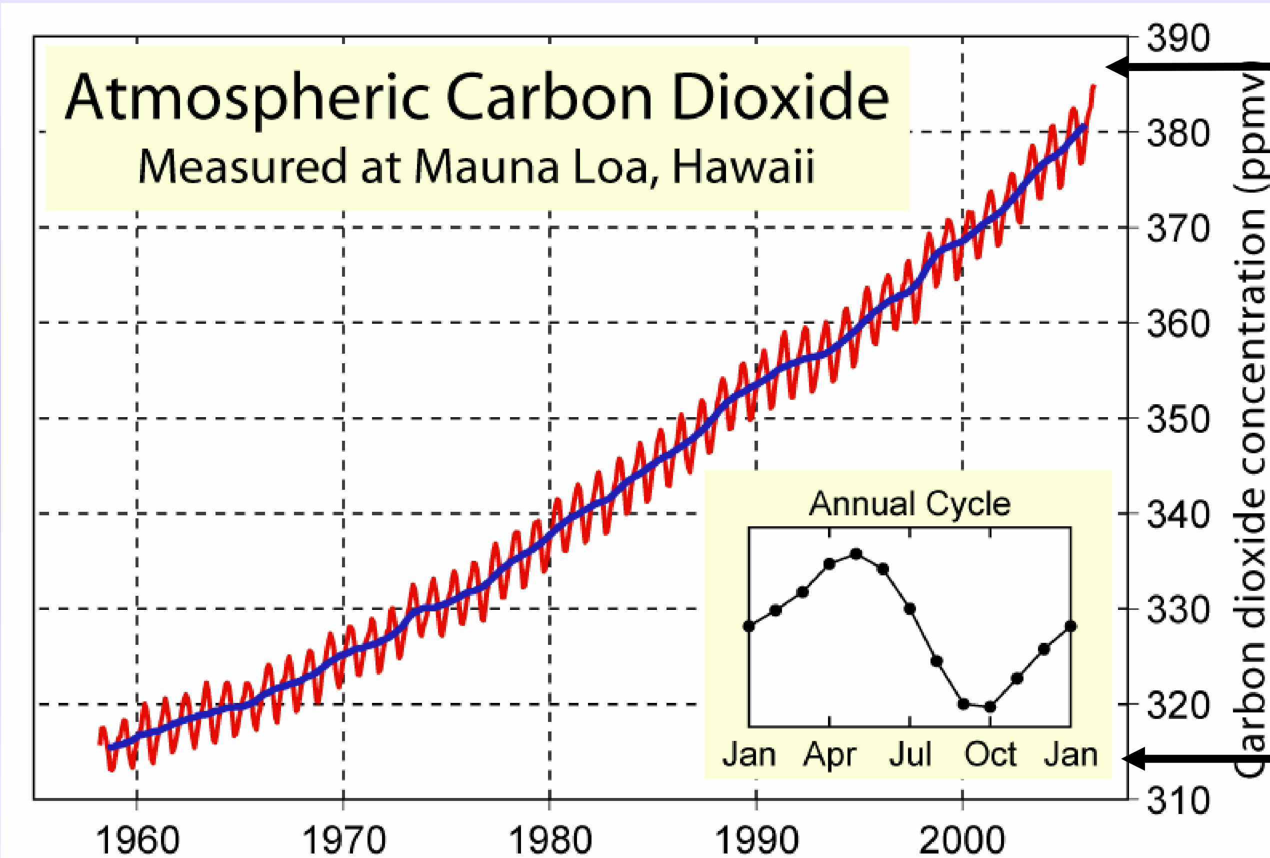
Radiative-convective climate models

- The (globally averaged) vertical temperature profile can be simulated with a *radiative-convective climate model* (RCM)
  - Convection occurs when the radiative lapse rate (dT/dz) exceeds the critical lapse rate for convection, often taken to be a *moist adiabat*
- Doing more complicated climate calculations requires a 3-D *general circulation model* (GCM), also called a global climate model



- Of course, the big news today is that atmospheric CO_2 is going up…

Keeling curve (Mauna Loa)



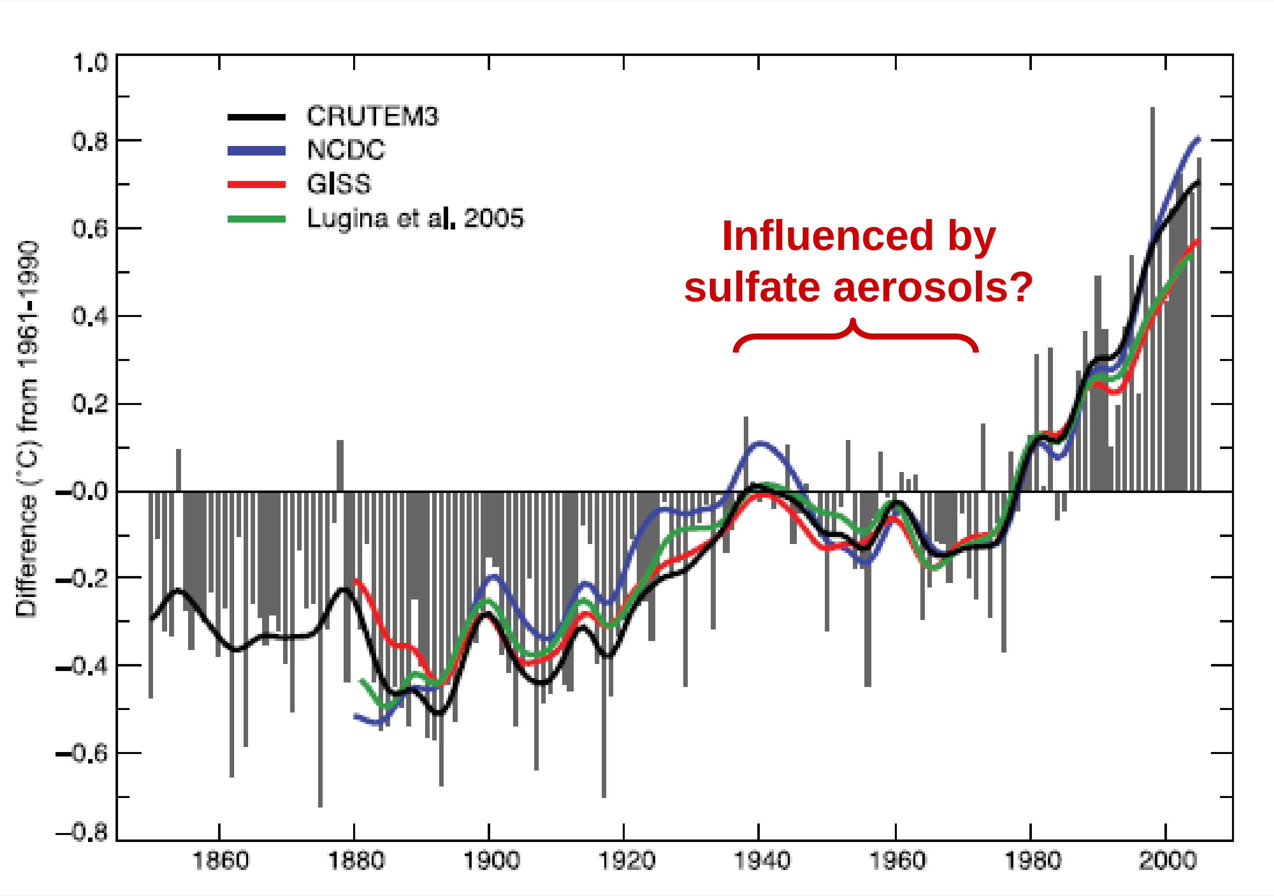
387.8 ppmv
(July, 2008)

315 ppmv
(1958)

Source: http://scrippsco2.ucsd.edu/
(Graph from Wikkipedia)

- And this leads to global warming…

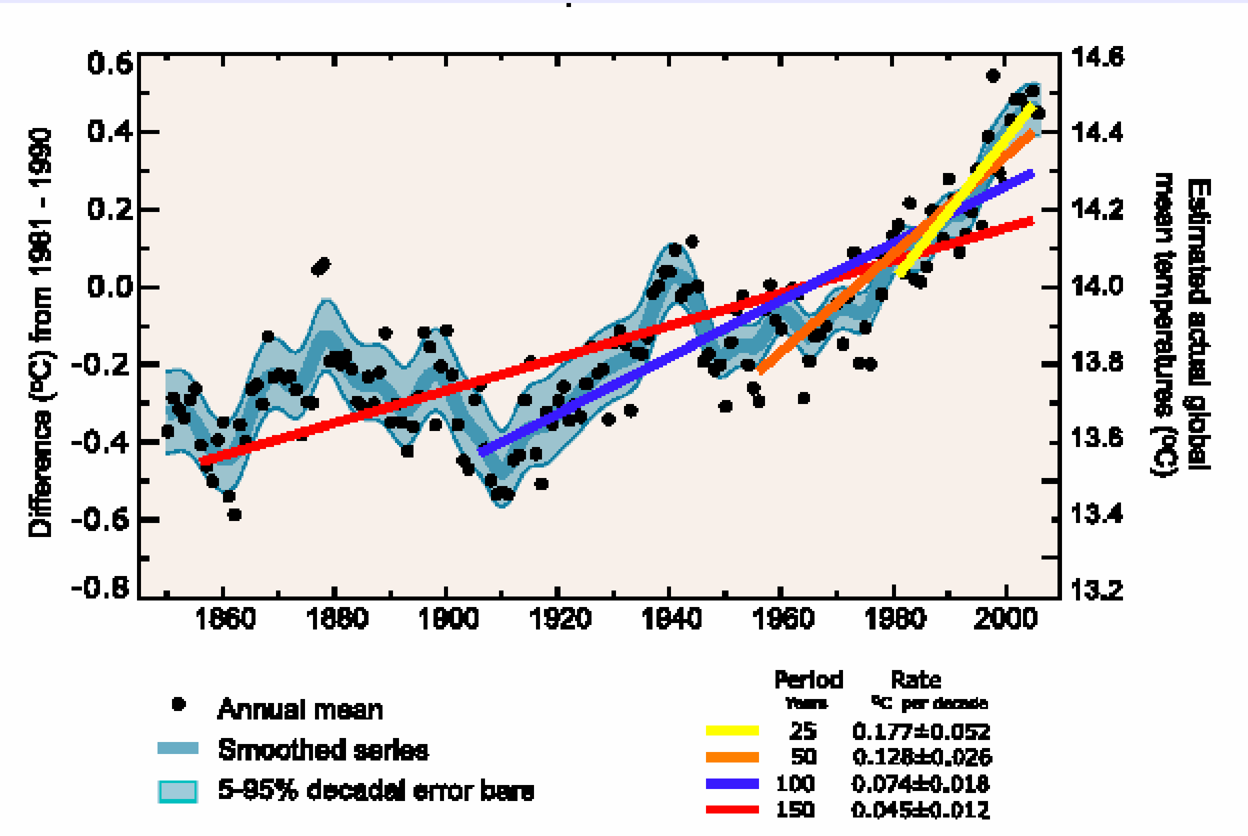
Recent surface temperatures



Source: IPCC 2007 report, Ch. 3, p. 241

See also Kump et al., *The Earth System,* ed. 3, Fig. 1-4

Surface temperature trends

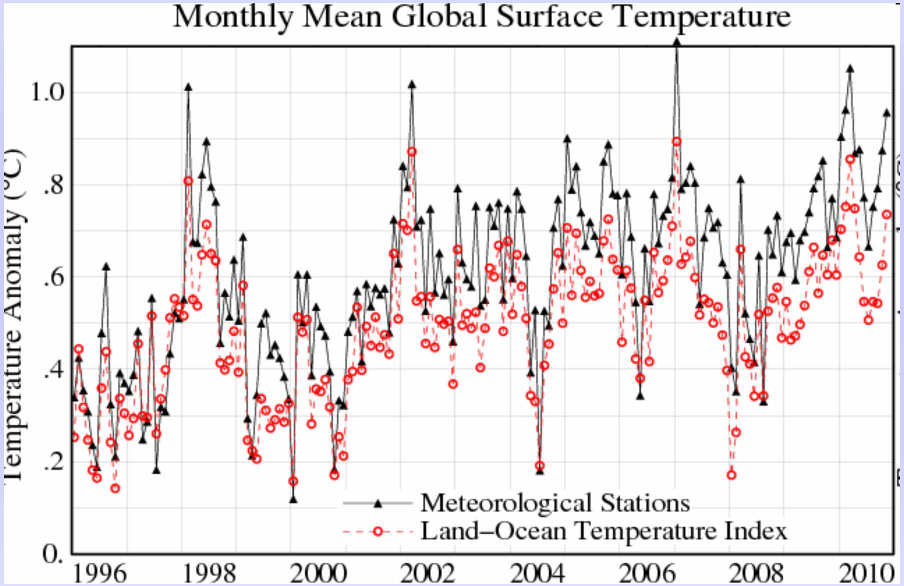


Source: 2007 IPCC report (http://www.ipcc.ch/)

- There is also statistical evidence that the *rate* of surface temperature increase is also increasing

Mean surface temperatures: the last 14 years

- <u>Q</u>: How do skeptics get around the data?
- <u>A</u>: They point out that if you start counting in 1998, there has been little or no net warming since that time…



http://data.giss.nasa.gov/gistemp/graphs/

Conclusions

- The greenhouse effect can be accurately calculated using 1-D or 3-D climate models
  - The physics of absorption of IR radiation by CO_2 and H_2O is well understood but still difficult to parameterize in a time-efficient manner
- In spite of this, climate remains *hard to predict*, because of the effects of clouds and other nonlinear processes (not discussed here) in Earth's climate system