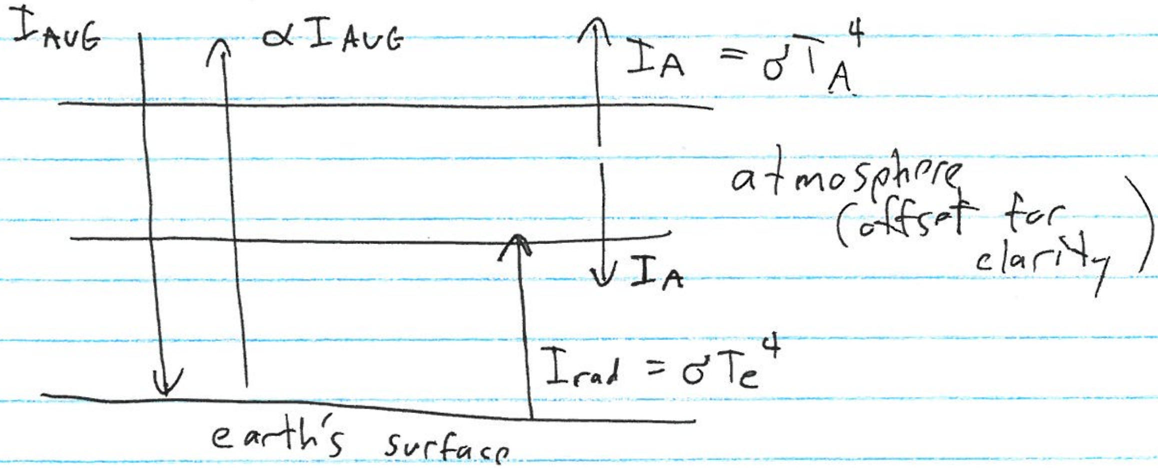
Greenhouse Effect

Estimate Earth's temperature including atmosphere

Assume the atmosphere absorbs 100% of the earth's thermal radiation (overestimates)

Modified model:



As before: Sun's short wavelength light is incident on the surface: $I_{AVG} = \frac{I_0}{4} = 342 \frac{W}{m^2}$

of this αI_{AVG} is reflected with $\alpha \sim 0.31$

As before, the earth radiates $I_{rad} = \sigma T_4^4$ but now all of this is absorbed by certain "greenhouse gases": chiefly H_2O and CO_2

The atmosphere is also made of matter and radiates with $I_A = \sigma T_A^4$ in both directions up and down.

Important point: the energy flow from the atmosphere comes entirely from the radiation emitted by earth

$\therefore \quad 2I_A = I_R \qquad \therefore I_A = \frac{I_R}{2} = \frac{\sigma T_E^4}{2}$

Now look at the total energy balance

Net heat in to earth $= I_{AVE}(1 - \alpha)$

(↑ in, ↑ reflected)

Net heat out $= I_A = \frac{\sigma T_E^4}{2}$

$$\therefore \quad I_{AVG}(1-\alpha) = \frac{\sigma T_E^4}{2}$$

↑ before we did not have this

$$\therefore \quad T_e^4 = 2\,\frac{I_{AVG}(1-\alpha)}{\sigma}$$

$$T_e = \left(\frac{2 \times 342\,\frac{W}{m^2}\,(1-0.31)}{5.67 \times 10^{-8}\,\frac{W}{m^2 K^4}}\right)^{\frac{1}{4}}$$

$$= \underline{\underline{299\,K}}$$

(higher than previous value by $2^{\frac{1}{4}}$)

Somewhat higher than average value of: $\underline{\underline{286\,K}}$

This is a highly simplified model but nevertheless comes reasonably close.

We have overestimated the amount of absorption

We can understand the greenhouse effect as follows :

① Suppose the atmosphere did not absorb outgoing radiation.
Then the earth would be at $T = 258K$ as before (neglecting atmosphere)

② Now imagine turning on the absorption.

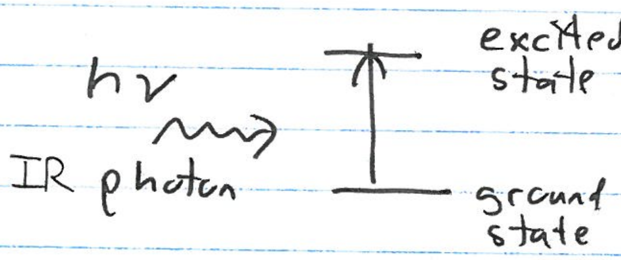
This suddenly reduces the outgoing radiation from earth, while the incoming radiation is unchanged.

③ This means there is net heat into the earth, so the atmosphere must warm and hence the earth's surface as well.

Absorption of radiation by the atmosphere

How justified are the previous assumptions?

Gas molecules can absorb energy from light via internal energy levels:
- electronic
- vibrational
- rotational



end result: photon in = heat out

When light passes through an absorbing medium its transmitted intensity is reduced by an exponential relation often called

Beer's Law: $I = I_0 e^{-kz}$ (transmitted light)

where z = the path length of the light through the absorbing medium i.e. the atmosphere

k = the absorption coeffient which depends on

(1) the identity of the absorber (eg. CO_2, H_2O, O_3...

(2) the concentration of the gas.

(3) the wavelength of the radiation λ.

If T = the fraction of light transmitted,
the fraction absorbed $A = 1 - T$
(This leads to a nonlinear dependence of absorption on concentration)

Example of absorption by atmospheric gases:

The following figure shows the energy spectrum of the sun at the top of the atmosphere, and at the earth's surface.

We see a reduction in overall transmission intensity partly caused by reflection (recall $\alpha \sim 0.31$)

We also see some dips due to absorption by gases, chiefly O_3, H_2O

Most of these dips are far from the peak and so our assumption that the atmosphere does not absorb solar radiation is pretty good.

At very short wavelengths O_3 blocks most of the UV, but this is not where most of the power is located.
(O_3 is important in limiting our exposure to UV)

Note: the absence of any CO_2 absorption

Absorption of earth's thermal radiation by atmosphere

Next : focuss on radiation leaving the earth from thermal radiation from the surface

Following figure shows :

(1) upper curve : total absorption from all atmospheric gases.
- Note the lack of absorption in the region around the sun's peak output.
- Note the strong absorption around the earth's emission region

* - ~ 70% of earth's emission is absorbed primarily by water vapour

(2) + (3) Next two curves show absorption spectra for O_3, water, and CO_2.

water has the strongest effect, followed by CO_2.
Note that CO_2 has some bands in places where water is transparent e.g. 8 - 11 μm

This is where CO_2 concentrations can contribute to global warming.

The following table shows the contributions of the top 5 greenhouse gases to the current warming effect (neglecting human effects)

- H_2O has the highest concentration (average value since it is condensable & varies widely at the local level)
- H_2O is responsible for ~ 20.6°C of the current average temp increase compared with the zero atmosphere situation

- CO_2 is present in ~ 10X lower concentration but contributes 7.2°C, indicating that it is a more "potent" greenhouse gas

* Note the absence of nitrogen even though it constitutes ~78% of the atmosphere.

Evidence for global warming (IPPC 2007)

- best estimate ~ 0.7°C over past 100 yrs
- note : locally much higher in arctic.

Viewgraph : IPPC temp. data

Climate Modelling :

- extremely complex
- outside the scope of this course

Problems :

- H_2O concentration varies with surface temperature widely
- Convection
- Feedbacks : e.g.
  - Positive feedback — melting ice reduces albedo (α) ⇒ warming
  - Negative feedback — warming increase evaporation which reduces albedo ⇒ cooling

Viewgraph : Various IPPC 2007 scenarios.

Beer's Law example

Recall transimitted IR radiation is given by

$$I = I_0 e^{-kx}$$

where I_0 = radiation emitted at surface

x = distance above surface

k depends on - λ
- concentration of species

Assume uniform atmosphere w/ thickness h

Suppose for a given λ we have

$$I = I_0 e^{-k_0 h}$$

k_0 = initial value of k

suppose k is such that $I = \frac{I_0}{2}$

i.e. $\frac{1}{2}$ of surface radiation is transmitted

$$T = \frac{1}{2} \qquad A = 1 - \frac{1}{2} = \frac{1}{2}$$

Now suppose we double the concentration of greenhouse gas: $k \to 2k_0$

Because of the exponent, $I = \frac{I_0}{2^2}$

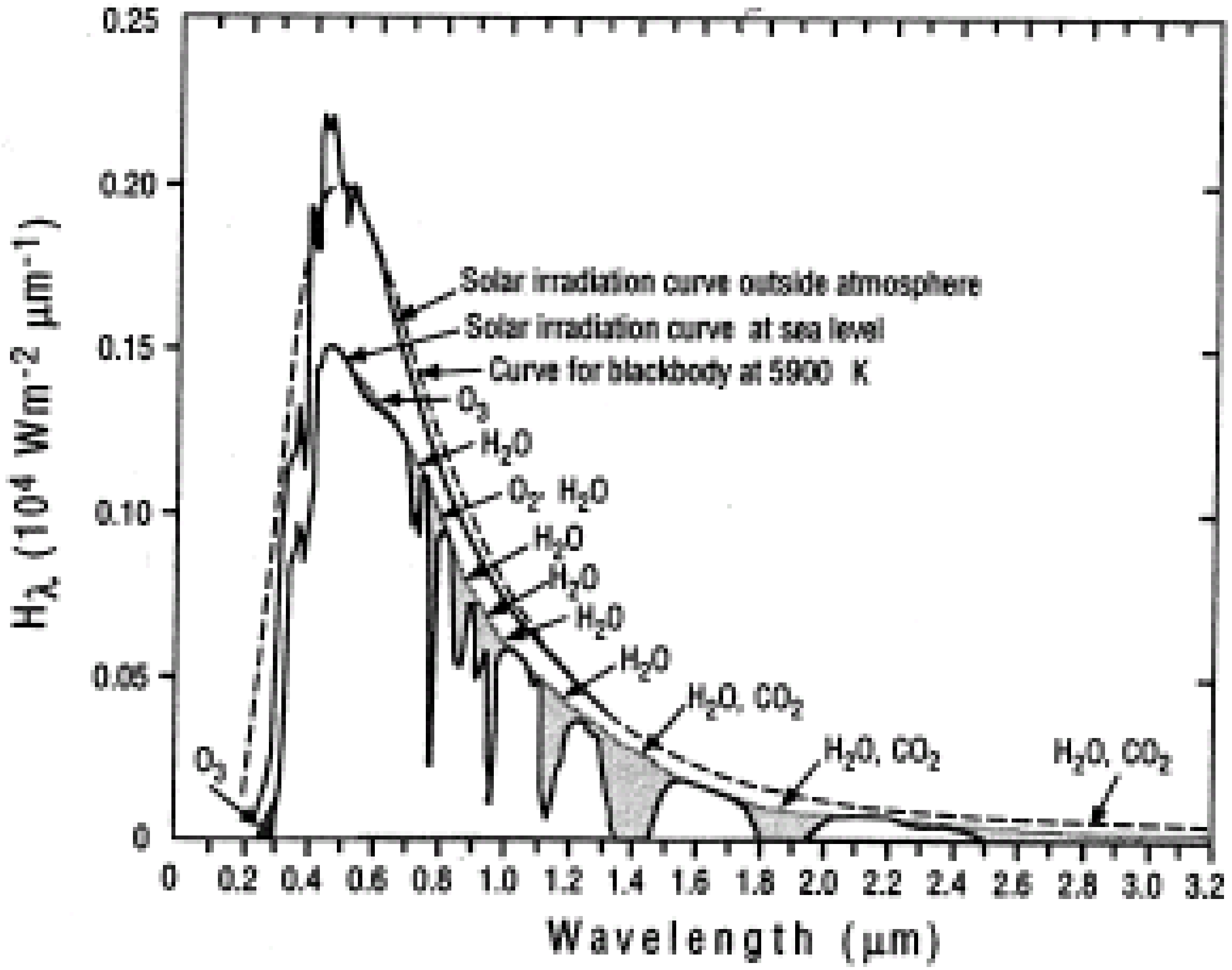
$$I = I_0 e^{-2k_0 h} = I_0 \left(e^{-k_0 h}\right)^2 = I_0 \left(\frac{1}{2}\right)^2$$

$$\therefore \; T = \frac{1}{4} \quad \text{but } A = 1 - \frac{1}{4}$$

* So, double of CO_2 does not lead to a doubling of absorbed power ...

try for $k \to 4k_0$

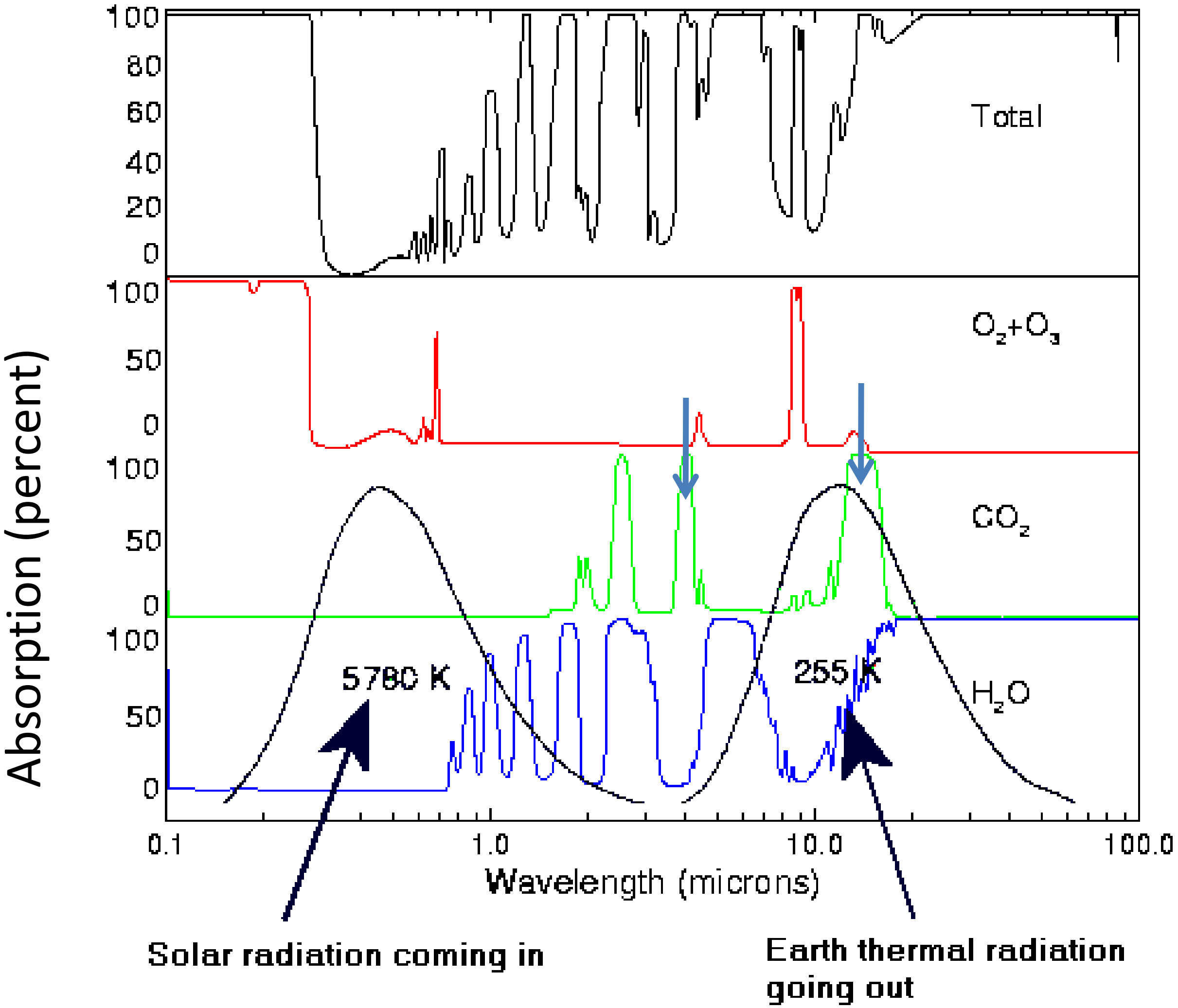
Solar region: absorption by the atmosphere:



Conclusion: atmosphere is largely transparent to visible radiation

From Boeker and van Grondelle ``Environmental Physics`` (1995)

Absorption of important atmospheric gases



Down arrows indicate CO_2 bands in H_2O windows

Note strong absorption bands due to water

Note the "window" in H_2O absorption at 8-14μm

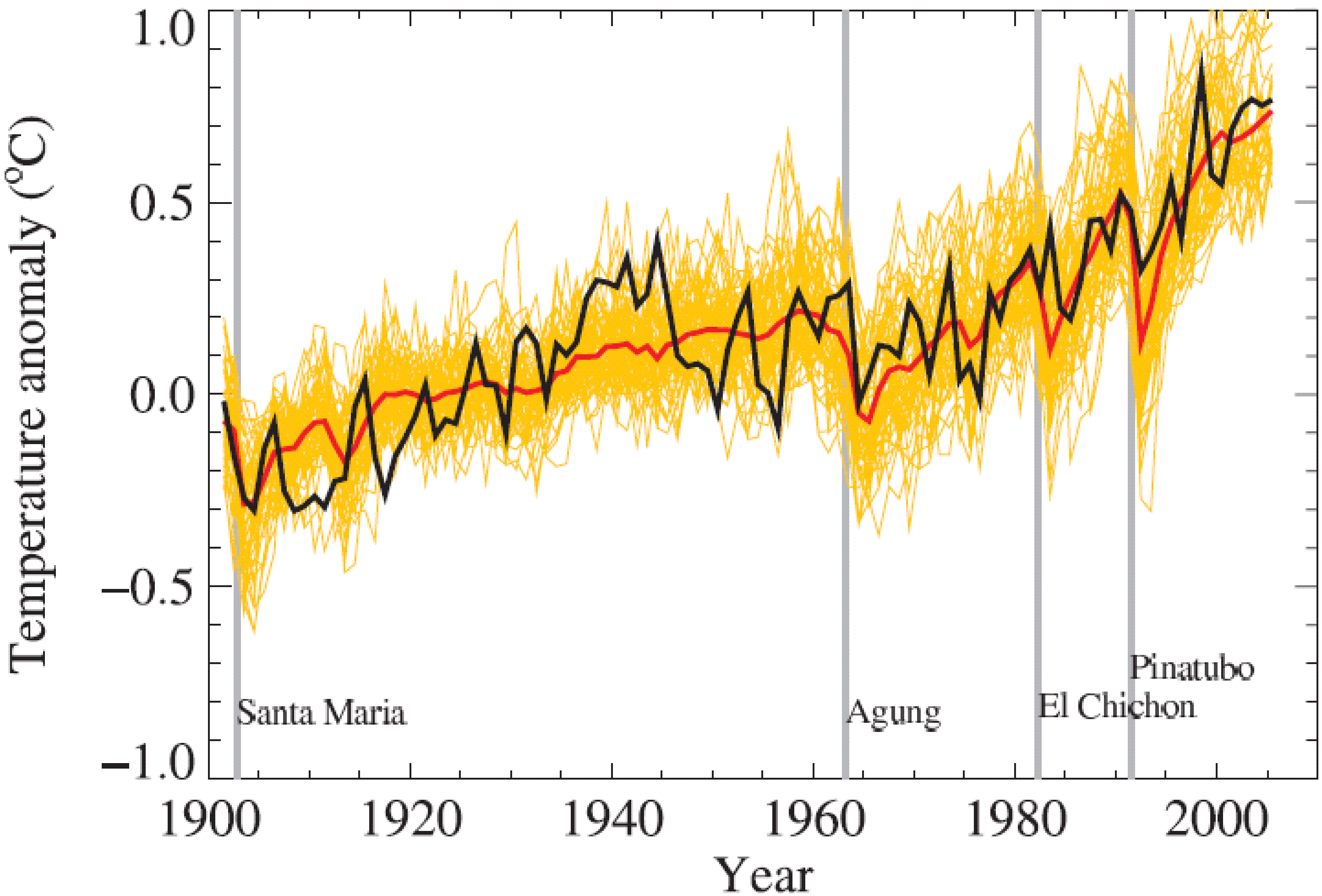
http://www.bwebcentral.com/articleswap/viewarticle.php?uID=466

Breakdown of warming effects of various greenhouse gases

Trace gas	Present concentration (ppm)	Present warming effect (°C)
H_2O vapour	$2\text{-}3\times10^3$	20.6
CO_2	345	7.2
O_3 (troposphere)	0.03	2.4
N_2O	0.3	0.8
CH_4	1.7	0.8

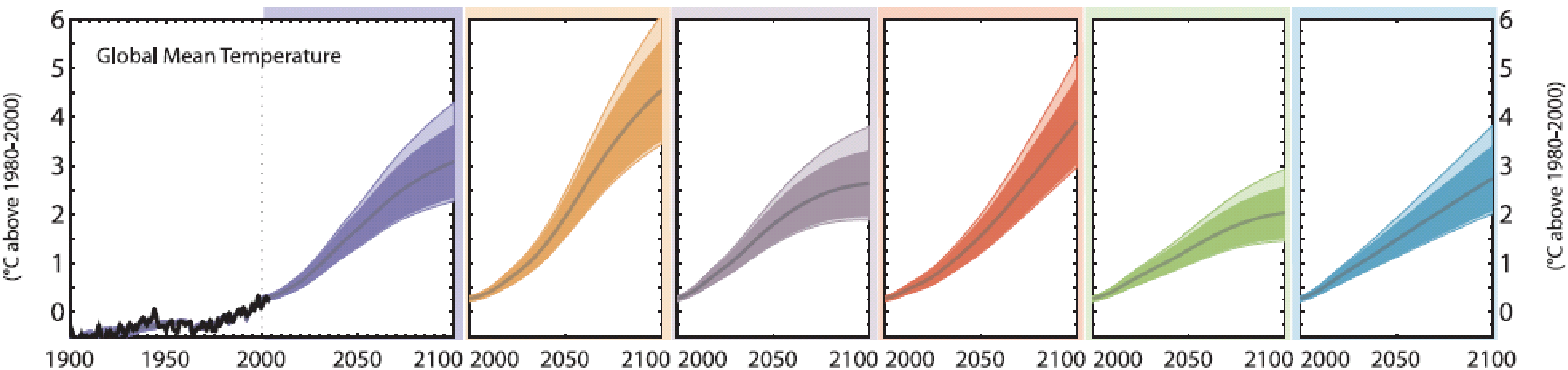
From Boeker and van Grondelle
``Environmental Physics`` (1995)

Evidence for Global Warming



Intergovernmental Panel On Climate Change: 4th Assessment Report, Ch. 8 (2007)

IPCC 2007 Model Summary: Projected temperature increase



Intergovernmental Panel On Climate Change: 4th Assessment Report, Ch. 10 (2007)