EM Radiation and the Greenhouse Effect

As you are no-doubt aware, the greenhouse effect has become a major global issue. As usual, we will try to keep our attention on the physics. What **is** the greenhouse effect? Where does it come from? Does the greenhouse effect exist on Earth? Is it possible that humans contribute to an Earthly greenhouse effect?

It is the sense of the scientific community that carbon dioxide from unrestrained combustion of fossil fuels potentially is the most important environmental issue facing mankind.
-U.S. Department of Energy, report, 2 Apr 79 (unverified)

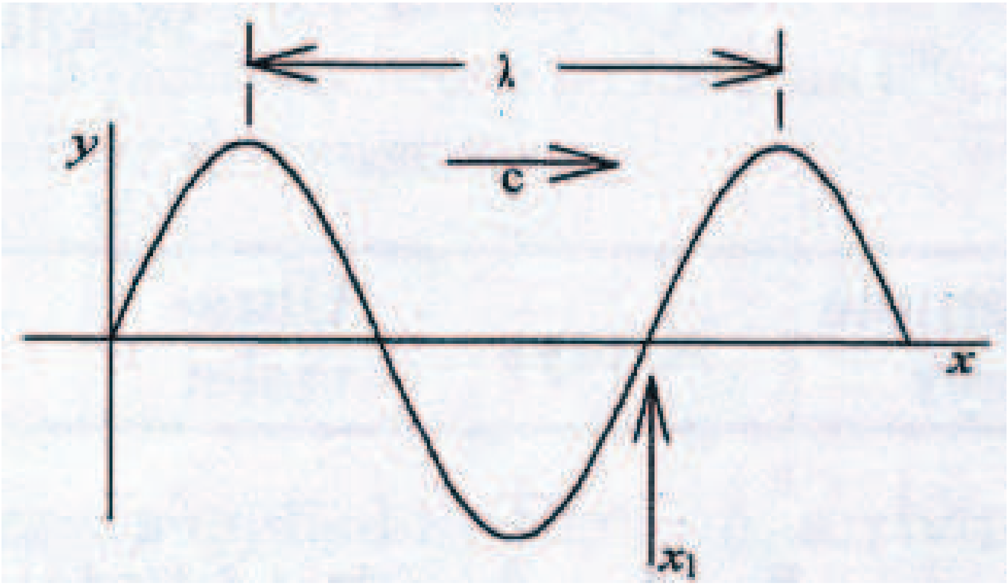
The whole (global warming) thing is created to destroy America's free enterprise system and our economic stability - Jerry Falwell (unverified)

EM Spectrum

We have already studied conduction and convection as ways to transport heat, now we turn to radiation.

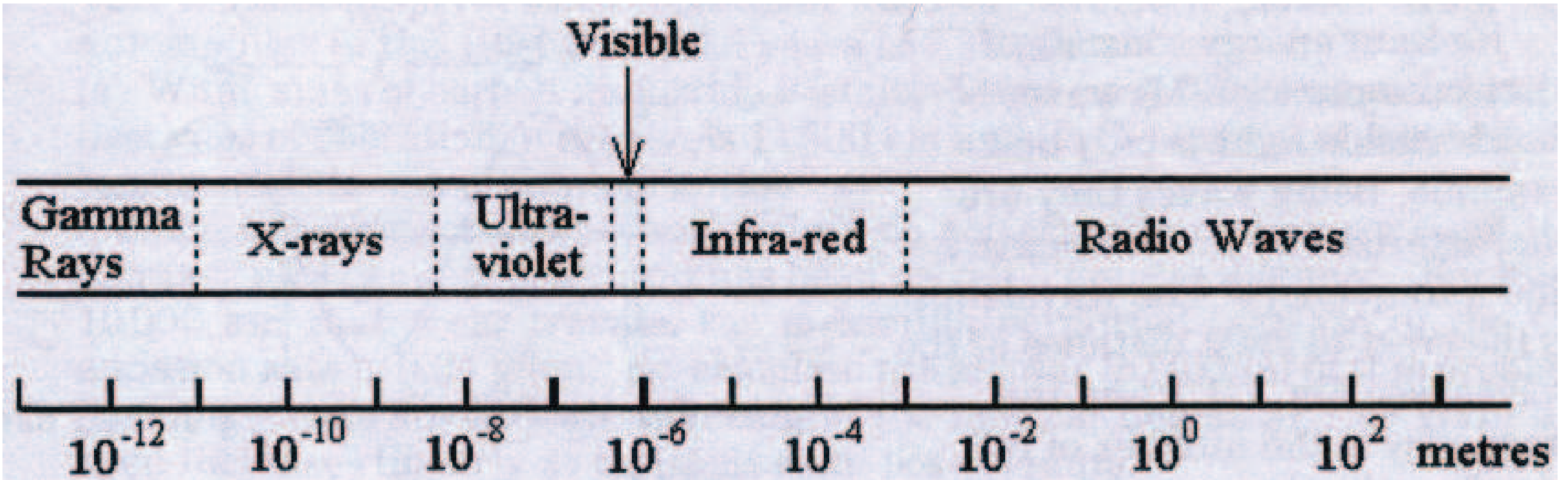
Radiant energy consists of EM waves characterized by a specific wavelength (λ in m) and frequency (f in Hertz) and speed ($c = 2.998 \times 10^8$m/s). These three quantities are related by

$$c = f\lambda$$



EM Spectrum

The EM Spectrum refers to the range of EM wavelengths:



This is a big variation: visible light is 700-400nm, radio waves are greater than 10cm. We have already discussed how various pollutants in the air can absorb specific frequencies of visible light (eg. photochemical smog). The selective absorption of specific parts of the EM spectrum is key to the greenhouse effect.

Inverse-Square Law

The intensity of radiation varies with distance from the source by a so-called inverse-square law. In other words, if you move twice as far away from the source you feel only 1/4 of the intensity.

Intensity is defined as the amount of power passing through a unit of area. A point source of radiation will emit in a sphere, so

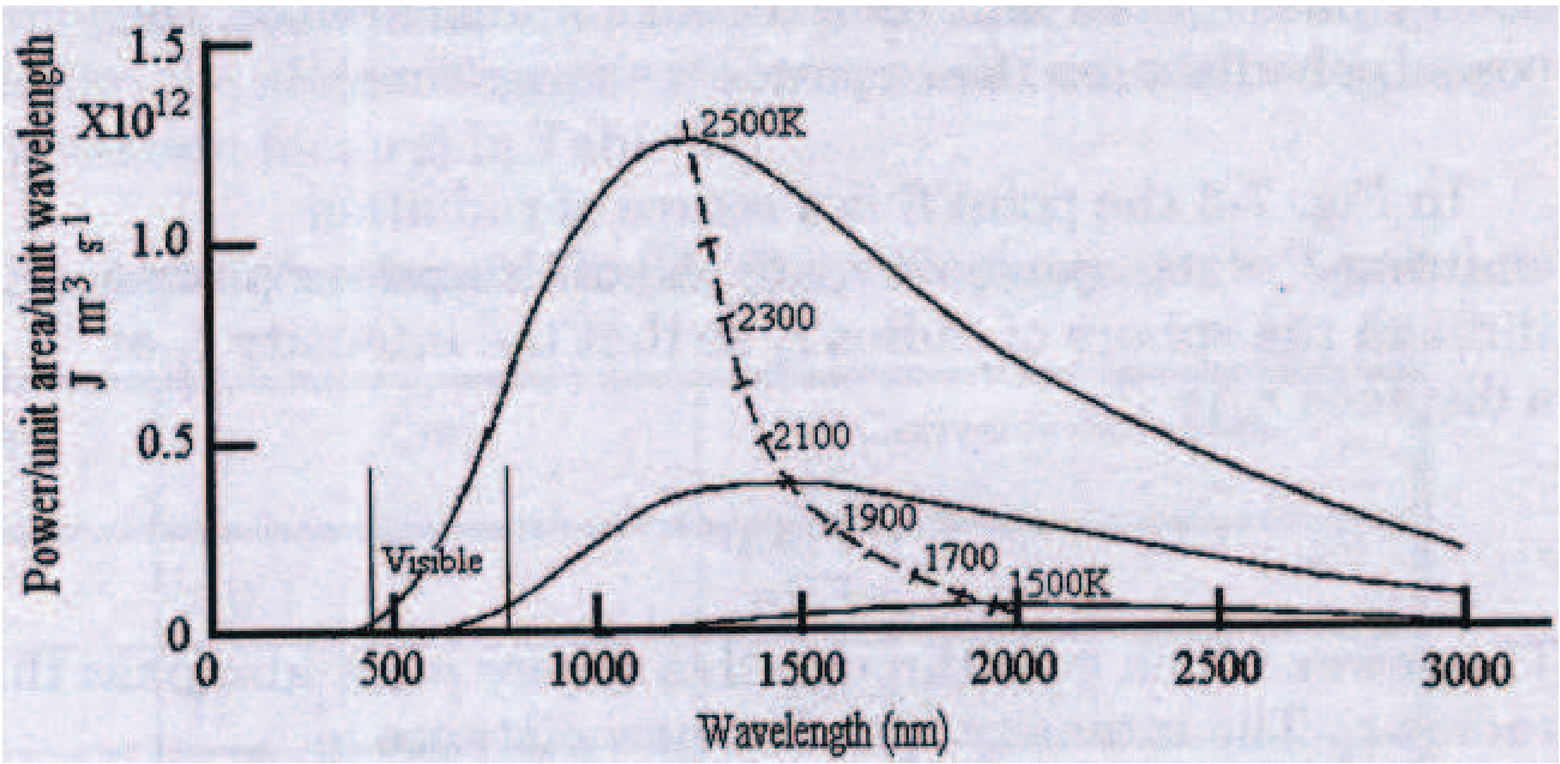
$$I = \frac{P}{4\pi r^2}$$

If you calculate this intensity for two concentric spheres you can see

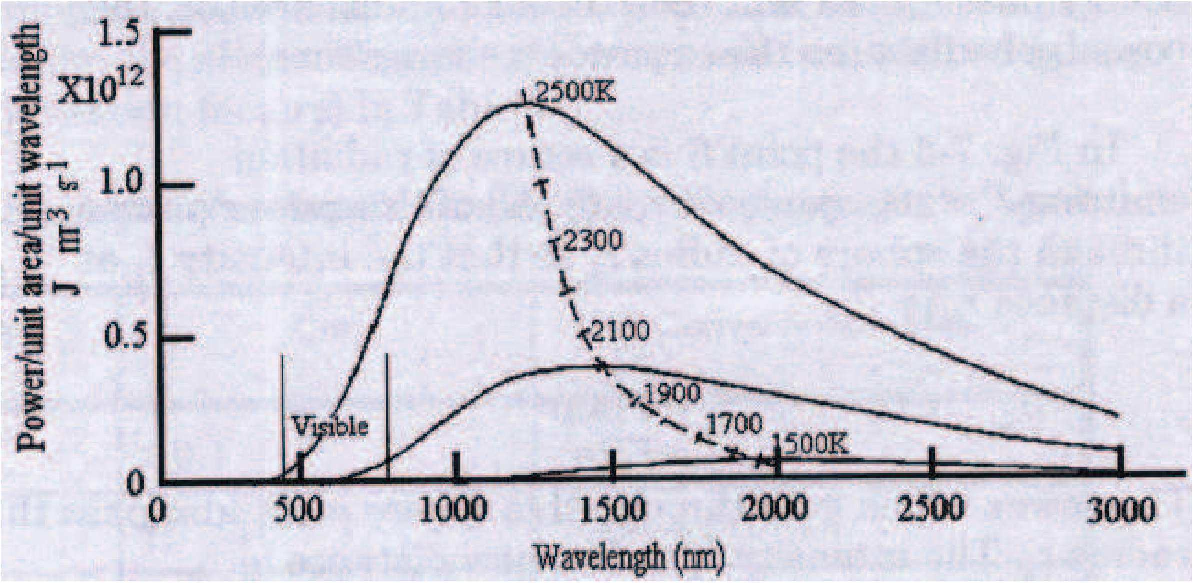
$$\frac{I_1}{I_2} = \left(\frac{r_2}{r_1}\right)^2$$

Blackbody Radiation

How is EM radiation distributed over the available wavelengths? Is most of the energy in the visible? Microwave? We need to look at a blackbody spectrum.



Blackbody Radiation - Stefan's Law

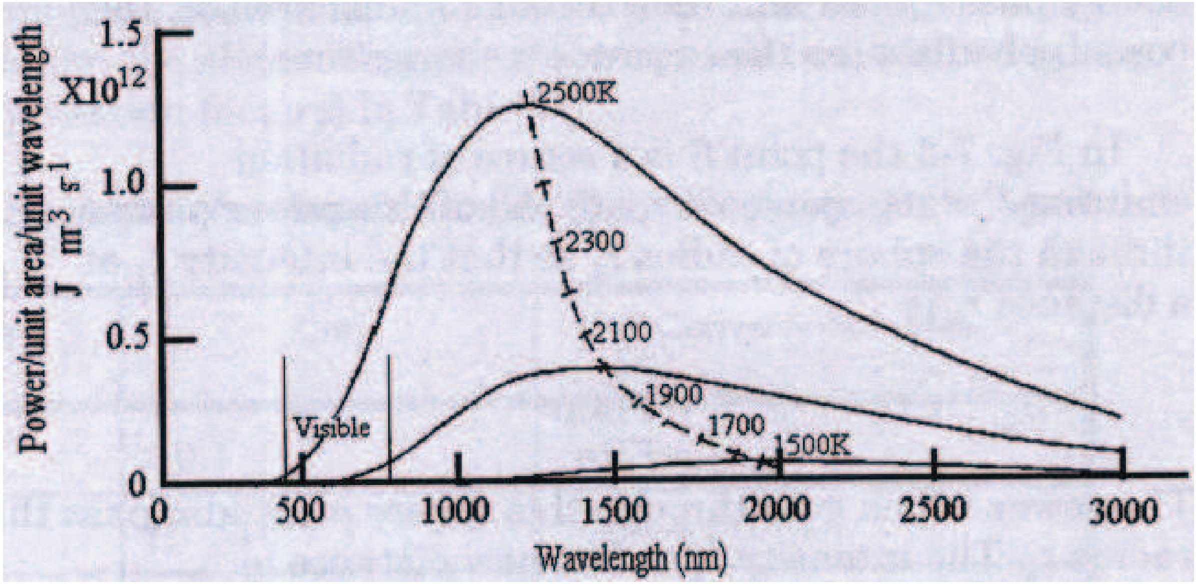


The area under the curve is the total intensity radiated by an object at temperature T. As the temperature of an object increases, its energy output increases at every wavelength. This increase in intensity is given by Stefan's Law

$$I(T) = \epsilon \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8} W \cdot m^{-2} \cdot K^{-4}$ and ϵ is the average emissivity.

Blackbody Radiation - Wein's Law



Also notice that the position of the peak changes with temperature. High temperatures peak at small wavelengths and vice versa. The peak of the radiation is given by Wien's Law

$$\lambda_m(nm) = \frac{2.8972 \times 10^6 nm \cdot K}{T(K)}$$

The Sun radiates as a blackbody at 6000K, giving a peak at about 500nm.

Blackbody Radiation - Planck's Radiation Equation

Fully understanding this curve requires quantum mechanics. In QM, radiation is a "rain" of massless particles (quanta) carrying energy and travelling at the speed of light. The energy of each quantum is given by Planck's equation

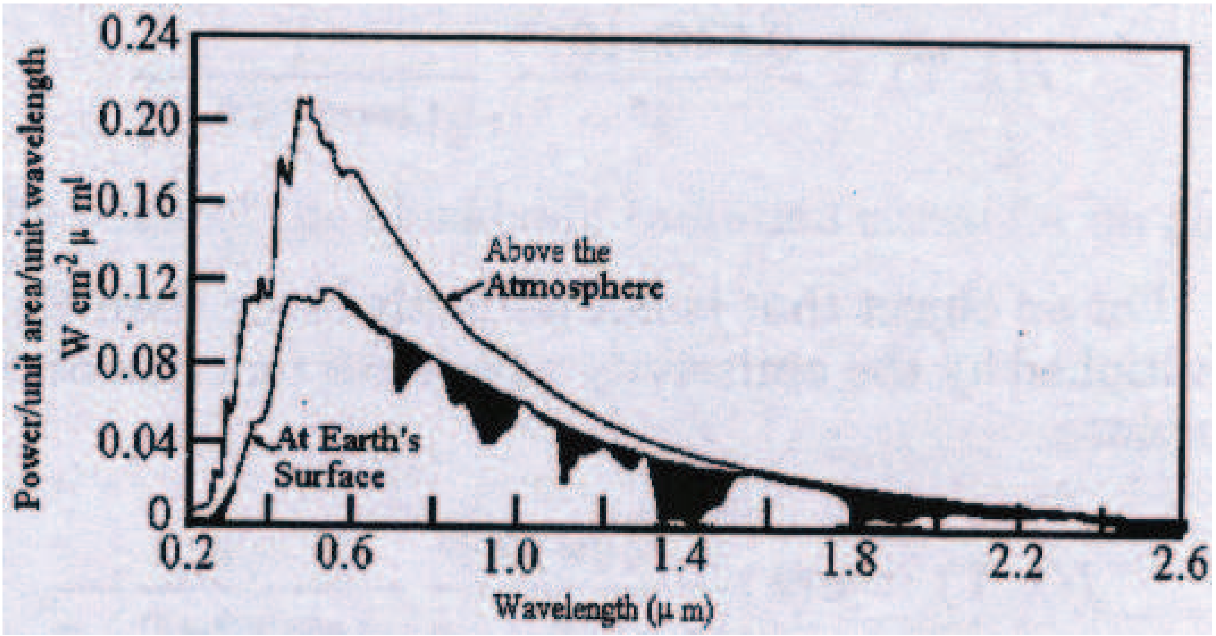
$$E = hf$$

where $h = 6.626 \times 10^{-34} J \cdot s$ is Planck's constant. The blackbody radiation curve is then described by Plank's Radiation Equation

$$I(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda k_B T} - 1}$$

where k_B is Boltzmann's constant.

Solar Radiation



You can see from this curve that solar radiation follows a blackbody spectrum if you observe it above the atmosphere.

The second curve is measured under the atmosphere. Same shape but lower intensity as some radiation is reflected (albedo $= \alpha = 0.35$). Several regions of the second curve are "eaten away" by absorption of radiation by airborn molecules (eg. H_2O and CO_2). About 18% of incident solar energy is absorbed this way.

Energy Balance in Earth's Atmosphere

The way in which the Earth achieves its normal cozy temperature is rather complex. If we just calculate the temperature of the Earth, neglecting the atmosphere, we would get about $-18°$C. Our atmosphere of particles acts as a blanket to keep us warmer than that. The specific gasses which provide this insulation are called "greenhouse gasses". These gasses generally share the feature that they largely transmit radiation at short wavelengths and absorb at long wavelengths.

Energy Balance in Earth's Atmosphere

The general way this works:

- solar radiation strikes the atmosphere, 35% is reflected, the rest continues
- part of the remaining energy is absorbed by the atmosphere, part reaches the Earth's surface
- the atmosphere then re-radiates in all directions
- the Earth's surface re-radiates
- radiation from the Earth's surface gets partially absorbed in the atmosphere and partially radiated into space
- the atmosphere re-radiates in all directions
- radiation from the atmosphere warms the Earth, causing it to radiate more heat, which goes into the atmosphere, which then....

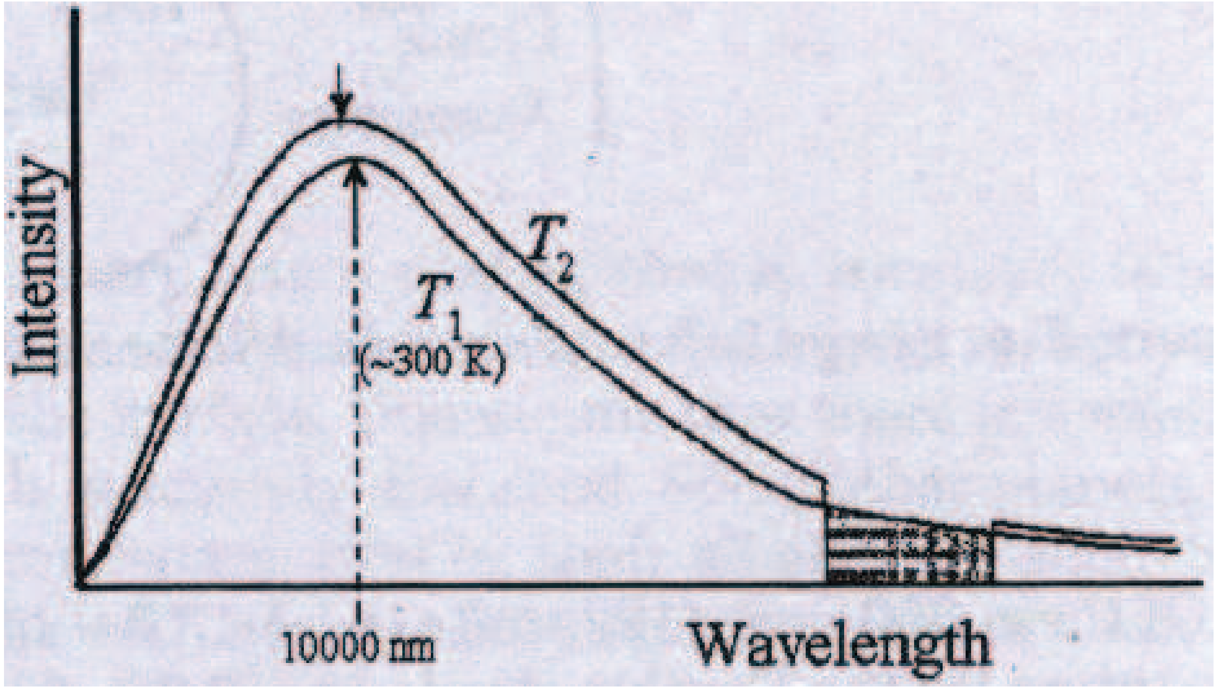
Energy Balance in Earth's Atmosphere

Now, all this needs to be at equilibrium (balanced). The surface of the Earth will be receiving more energy than it radiates because it keeps getting energy back from the atmosphere. So, the surface will continue to warm until it reaches the temperature at which the energy fluxes balance. This is a pretty complex process. What happens if you "tweak" it by, say, changing the absorption of radiation in the atmosphere???

The Greenhouse Effect

The previous description is, in fact, what happens in a greenhouse

- place a piece of glass between the sun and your plants
- the glass transmits most of the short-wavelength sunlight but absorbs certain (infra-red) wavelengths
- the glass then heats-up and radiates power back into the greenhouse
- the temperature in the greenhouse rises until equilibrium is reached



The Greenhouse Effect on Earth

So, we definitely have a greenhouse effect....otherwise Earth would be unpleasantly cold. The gasses that give us the effect are primarily H_2O and CO_2. We can do some estimation of the size of the effect with some relatively simple reasoning.

Let's call the total intensity of the Earth's radiation at the top of the atmosphere I_0. The total power incident on the Earth is then this intensity times the area it is incident upon: $\pi R^2 I_0$. While the solar radiation is only incident on the area of a circle, the Earth radiates all over the sphere so the average insolation is given by

$$I_0 \frac{\pi R^2}{4\pi R^2} = \frac{I_0}{4}$$

This leads us to an average solar energy input to our system of $350W/m^2$.

The Greenhouse Effect on Earth

We can use Stefan's Law and the known albedo to determine the temperature without an atmosphere (see page 6-9 of your book). If we introduce a simple model of the atmosphere:

- assume the Earth receives $(I_0/4)(1-\alpha)$ from the sun
- assume the Earth radiates an amount I_E which is completely absorbed by the atmosphere
- assume the atmosphere is an ideal blackbody which radiates I_A equally to space and the Earth

$$\begin{aligned} I_A &= (I_0/4)(1-\alpha) \\ I_E &= 2I_A = (I_0/2)(1-\alpha) \end{aligned}$$

since the Earth gets all the radiation from the sun and then gets all the radiation from the atmosphere too. Stefan's Law gives us

$$I_E = (I_0/2)(1-\alpha) = \sigma T_E^4$$

Solving for T gives 297K.

The Greenhouse Effect

So, we have a greenhouse effect. In fact, we would be quite unhappy without one! However, can we influence it at all? Can we significantly impact the concentration of greenhouse gasses in the atmosphere?

You have seen that several of our fossil fuel related activities pump CO_2 into the atmosphere. CO_2 is not normally considered a pollutant as it exists in our atmosphere already. But we are adding quite a bit of it to the atmosphere - about 9 billion tons/year! This output is increasing rapidly.

Atmospheric CO_2

This changes the atmospheric concentration of CO_2 substantially