CO2 is a greenhouse gas and a major contributor to climate change. CO2 has three absorption bands of electromagnetic energy centered at wavelengths of 2.7, 4.3, and 15 microns or wavenumbers of 3703, 2326, and 667 respectively.

The greenhouse effect of CO2 is a function of its molar density and the amount of the earth's radiant energy it can block. The following is a discussion of the behavior of the CO2 absorption bands in the atmosphere due to their interaction with the radiant energy of the earth.

Case 1: An atmosphere of pure CO2 with all three absorption bands saturated

A planet the size and mass of the earth, and about the same distance from a sun similar to the one that radiates energy to the earth is in a state of energy balance with incoming solar radiation. Suddenly an atmosphere with pure CO2 is introduced with sufficient CO2 to assure that the three CO2 absorption bands remain saturated no matter what conditions exist on the planet.

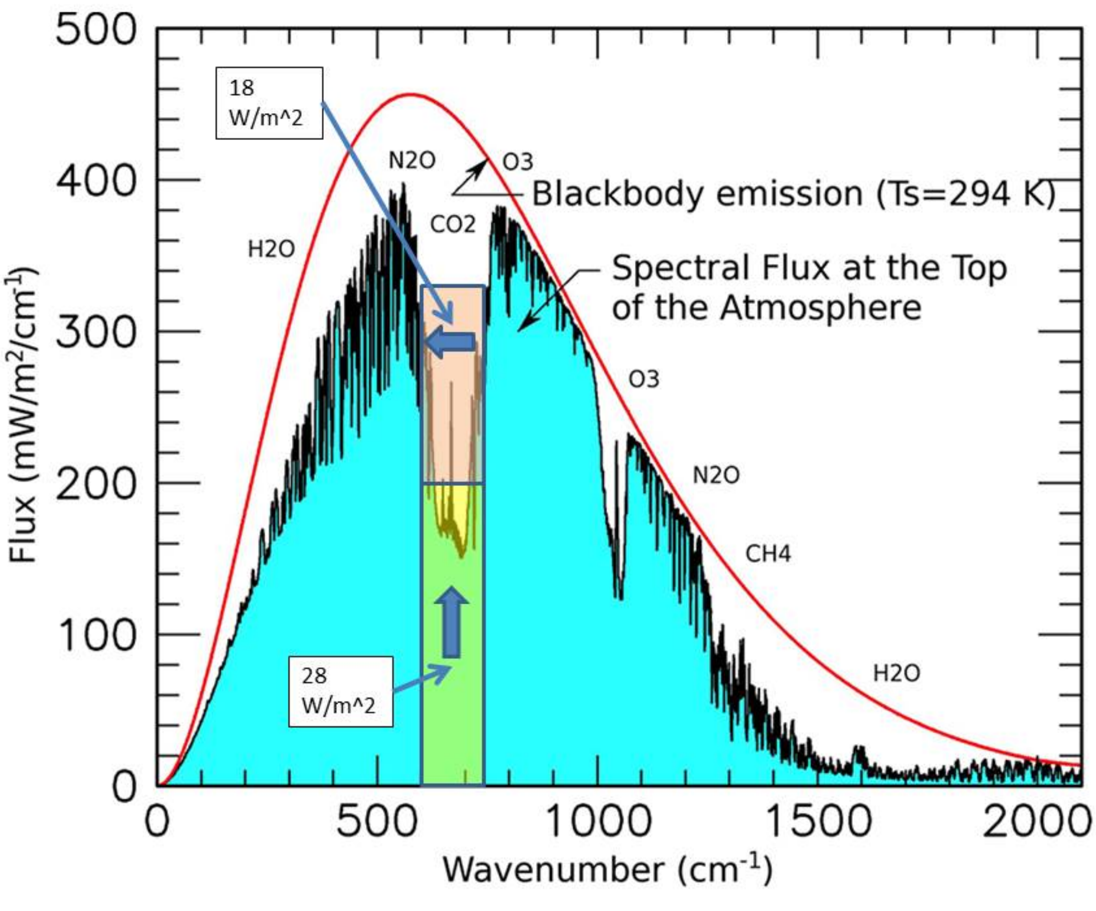

Figure 1: IR Spectrograph of the Radiant Energy of the Earth

Initially, this planet will be colder than the one represented in Figure 1. Its radiant energy curve will be lower and to the left of the one depicted. The radiant energy distribution curve shifts to the right with increasing temperature and every point on the curve is higher with increasing temperature. Photon production increases with increasing temperature and the photons produced have a shorter wavelength or longer wavenumbers.

The planet will have an energy imbalance as the result of CO2 reradiating energy it captures in its absorption bands. The planet's temperature will rise, and the radiant energy distribution will shift to the right. As it shifts, the radiant energy in the CO2 absorption bands will increase as long as the 15-micron band remains to the right of the energy distribution curve.

The planet's temperature rises as the 15-micron band marches toward the peak of the energy distribution curve. As the 15-micron band approaches the peak of the energy distribution curve, the rate of the rise of the reradiation caused by the CO2 absorption bands decreases until, at the peak, it is zero. The planet's rate of temperature rise also slows until it is zero at the peak. The planet's temperature stabilizes at the peak, and the planet's net energy balance approaches zero. When the 15-micron band reaches the top of the energy distribution curve, the planet's next incremental temperature increase will result in an incremental decrease in the radiant energy in the 15-micron band. At the peak of the radiant energy curve:

$$\frac{\partial E_{15M}}{\partial T} = 0 \qquad (1)$$

E_{15M} = Energy of the CO2 15-Micron Band
T = Temperature of the Planet

The peak of the energy curve is an equilibrium or steady-state point for the 15-micron band or any of the other two CO2 absorptions bands. To further increase the planet's temperature, the stability of the equilibrium at the peak of the planet's energy distribution curve will have to be overcome. Instead of being the cause of the temperature rise, the 15-micron band becomes the resistance to further temperature rises as the 15-micron band moves to the left of the radiant energy peak. The other two CO2 absorption bands and/or the addition of another greenhouse gas can cause further increases in the planet's temperature if the following condition is met:

$$\frac{\partial E_{ob}}{\partial T} > -\frac{\partial E_{15M}}{\partial T} \qquad (2)$$

E_{OB} = Energy from the 2.7, 4.2-Micron Bands

The equation says that the increase of energy with a temperature change in the other CO2 absorption bands must be greater than the decrease of energy with a temperature change of the CO2 15-micron band at an equilibrium point. This assumes no other greenhouse gas is added. While meeting this criterion, the resistance of the 15-micron band continues to decrease with temperature until the 15-micron band no longer has an impact on the planet's temperature. A steady-state point occurs when:

$$\frac{\partial E_{ob}}{\partial T} = -\frac{\partial E_{15M}}{\partial T} \qquad 3$$

If the 15-micron band is at the radiant energy curve peak, even a small amount of energy from the other two bands will push the 15-micron to the left of the peak, since at the peak of the radiant energy curve Equation 1 is governing, how far the 15-micron band moves to the left of the peak will be determined by Equation 3.

For the pure CO2 environment, whatever CO2 absorption band wavelength ends up at the peak of the planet's energy distribution curve sets the temperature of the planet.

At the conditions of this case, the 15-micron band is supersaturated at the radiant energy peak. Decreasing the CO2 molar density until the 15-micron band is just saturated would result in no change in the amount of reradiation. Decreasing the molar density further, and the band would be unsaturated. The amount of reradiated energy by the 15-micron band would decrease, and the planet's temperature would fall. In this case, the degree of saturation of CO2 15-micron determines the temperature of the planet. The temperature of the planet is a function of the degree of saturation of the 15-micron band.

Greenhouse gas absorption bands to the left of the peak of the radiant energy resist increases in planetary temperature. Greenhouse gas absorption bands to the right of the peak of the radiant energy curve drive increases in the planetary temperature.

Equations 1, 2, and 3 also apply to multiple greenhouse gases in the atmosphere. The sum of the radiant energy in the absorption bands of the greenhouse gases to the right of the radiant energy peak is driving the increases in the planetary temperature. The sum of the radiant energy in the absorption bands of the greenhouse gases to the left of the radiant energy peak resists those increases.

The above only considers the heating of the planet. The same analysis applies to the cooling of the planet except the driving forces are to the left of the radiant energy peak and the resisting forces are to the right of the radiant energy peak.

Case 1-A: Venus

Venus is about the same size and mass as the earth. Its temperature is 460 ^{o}C, and its pressure is 90 ATM. Venus's atmosphere is 97% CO2. Its atmosphere has a much greater molar density than earth's atmosphere.

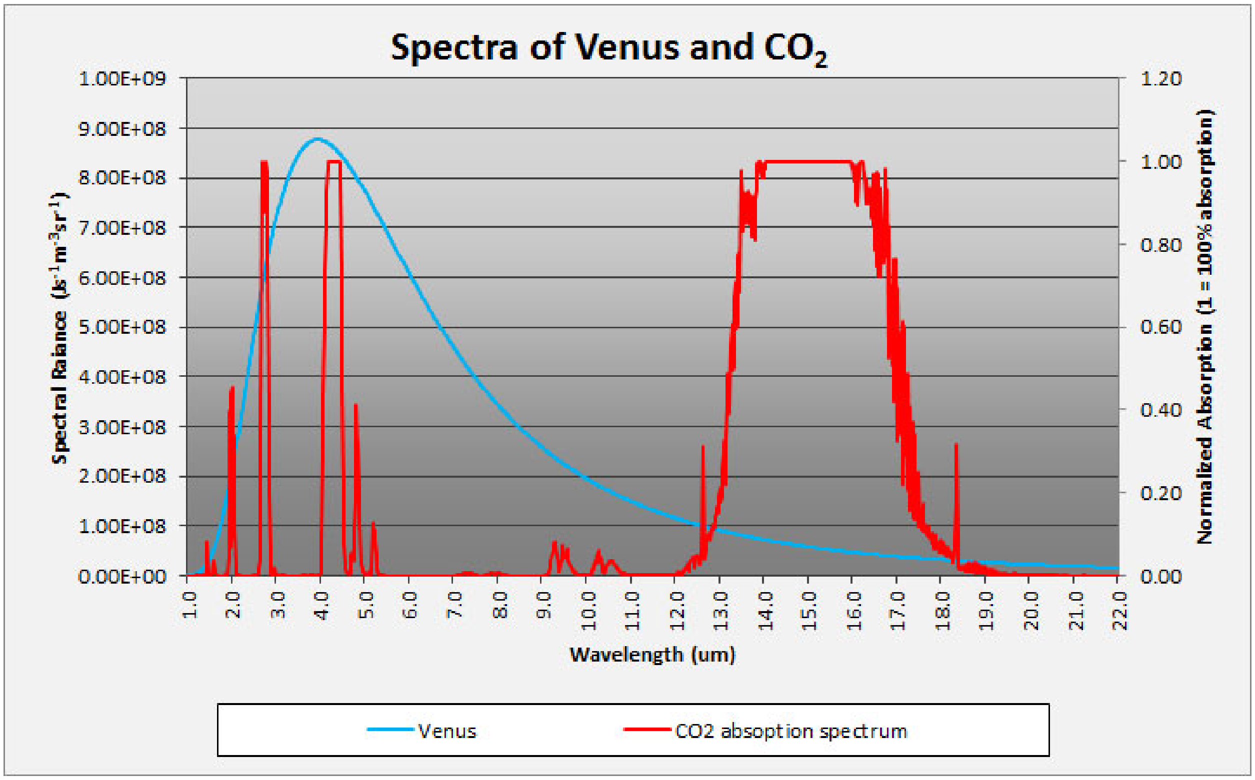

Figure 2: IR Spectrograph of the Radiant Energy of Venus

Venus's IR spectrograph uses wavelength as the independent variable. Venus's radiant energy curve shifts left as temperature rises on this spectrograph. That is the opposite of an IR spectrograph with wavenumber as the independent variable.

From the Case 1 results we can conclude:

1. The 15-micron band is saturated and far to the right of the peak of the radiant energy curve. It has no impact on the planet's temperature.

2. The 4.3-micron band is saturated and to the right of the peak of the radiant energy curve. It's resisting further increases in the planet's temperature.

3. The 2.7-micron band is saturated and to the left of the peak of the radiant energy curve. It is forcing the planet's temperature higher.

4. It appears Equation 3 is satisfied and the planet is at or near steady-state.

Case 2: The Addition of a Non-Greenhouse Gas

If N2 is added to the atmosphere described in Case 1, the only impact would be to dilute the molar density of CO2. That effect is partially offset by the effect of gravity. N2 does not absorb any significant radiation in the planet's IR radiation band. CO2 would behave identically to Case 1.

Case 3: The Addition of a Greenhouse Gas

If CH4 is added to the atmosphere in Case 1, it will dilute the molar density of CO2. It will also reradiate IR radiation in its absorption bands. Energy is a state function. The amount of energy to change a mass from an initial state to a final state is always the same regardless of path.

The initial state of the planet in Case 1 is somewhere to the right of the radiant energy peak. Introduce the same atmosphere as in Case 1 except the atmosphere contains a significant quantity of CH4. There is still enough CO2 in the atmosphere to saturate the CO2 absorption bands under all conditions. The CH4 band is unsaturated.

The CH4 and CO2 act independently of each other. The 15-micron CO2 band will march to the top of radiant energy peak as in Case 1. The CH4 band is also absorbing and radiating energy at an increasing rate as it moves toward the peak of the radiant energy curve. The additional energy from CH4 speeds the ascent of the 15-micron CO2 band to the peak. Since the amount of energy required to get the CO2 15-micron band to the peak is the same as in Case 1, the CO2 15-micron band moves left, past the peak of radiant energy curve and resists further movement caused by the CH4 band. The CH4 band is unsaturated, and that provides further resistance. That effect will be discussed in Case 4. The CO2 15-micron band will wind up somewhere to the left of the radiant energy peak.

H2O is a greenhouse gas that behaves differently from CH4. Its molar density is dependent on the temperature of the atmosphere. As temperature increases, the molar density of H2O increases. It has the same effect on CO2 as CH4, but its greenhouse effect is dependent on the atmospheric temperature increase that CO2 causes.

Case 4: An atmosphere of pure CO2 with the 15-micron band 50% saturated

Start with the same planet at the same conditions as Case 1. Add an atmosphere of pure CO2 with the CO2 15-micron band 50% saturated. No additional CO2 is added. Immediately the CO2 15-micron band begins to absorb and reradiate energy. The temperature of the planet begins to rise. The planet begins to radiate more energy in the 15-micron band, and the saturation level falls. It falls because of the increase in photons in the 15-micron band and the lower molar density of CO2 due to the higher temperature. As the planet’s temperature rises and the 15-micron band approaches the radiant energy peak, the increase of the energy with an increase in temperature in the 15-micron band decreases. For the temperature of the planet to keep increasing the following relationship must be met:

$$\frac{\partial E_{15M}}{\partial T} > \frac{\partial E_S}{\partial T} \qquad 4$$

E_S = Energy Escaping the Planet due to the Saturation Level of CO2

At an equilibrium point:

$$\frac{\partial E_{15M}}{\partial T} = \frac{\partial E_S}{\partial T} \qquad 5$$

When viewed as forcing functions and resistances, Equations 2, 3, 4, and 5 can be combined and expanded for all greenhouse gases. Add an equation that models the temperature inertia of the earth, and you would have a good representation of the greenhouse effect.