With this as a background, let's go on to talk about what turns out to be the principle absorbers and re-emitters of radiation in our atmosphere. First and foremost, we have water vapor. H2O is a bent triatomic molecule with a permanent dipole moment and pure rotational bands, as well as rotational-vibrational transitions.

Ozone, O3, like water, has a permanent dipole moment. It's also involved in photodissociation, that is the most energetic photons, the ultraviolet photons from the sun, can actually break apart, ozone molecules which result in the absorption of that energy. And carbon dioxide, which does not have a permanent dipole moment, so there are no pure rotational transitions. But it does have a temporary dipole moment during vibrational transitions. There are other more complex molecules, other greenhouse gases, nitrous oxide, N2O, and methane, CH4, are foremost among them.

Let's look at the distribution with altitude of some of these important greenhouse gases. This graph shows the concentration in parts per million by mass of various constituents of the atmosphere as a function of altitude, given on the scale on the left, or nearly equivalently pressure, in hectopascals, given on the scale on the right, pressure, of course, decreases monotonically upward in the atmosphere.

And so by far the most plentiful constituent near the surface is water vapor here, at well over 10 to the third parts per million. In fact, we measure water vapor near the surface in parts per thousand, typically. That decreases rapidly and approximately exponentially with altitude. So by the time we're up at 15 kilometers, there's hardly any water left. And by the time we're up into the middle of the stratosphere at 30 kilometers, it's pretty dry.

Carbon monoxide, which has much lower concentrations, to take another example, is fairly uniformly distributed in the troposphere, because the source of carbon monoxide is mostly near the surface, and then falls off quite rapidly into the stratosphere. Ozone exists in very low concentrations near the surface. It is variable in time. It's produced by photochemical reactions involving, man-made air pollution, for example, but it reaches quite large values in the middle stratosphere and plays a very important role in governing the temperature structure of the stratosphere as we'll see later on in the course.

There are three greenhouse gases that are approximately well mixed in this range of altitudes-- carbon dioxide, which has a very long lifetime in the atmosphere, and therefore, gets stirred around and mixed homogeneously, has a current concentration of about 400 parts per million; methane, here in red, which exists in much lower concentrations of about 1 part per million; and nitrous oxide here. Carbon dioxide is not as efficient a greenhouse gas as methane by a long shot. That is it's not as versatile a molecule, but there's much more of it than there is methane.

Water vapor is complicated, because not only does it vary with altitude, but as we'll discuss later in the course, it varies a great deal in space and in time. Here is a black-body emission curve for the atmosphere over wave number range of 0 to 2,000 inverse centimeters. So wave number is basically an inverse wavelength.

So we have our longwaves over on the left of this diagram, and shorter waves over here on the right. The red corresponds to the black-body emission curve for a typical surface temperature of 294 degrees Kelvin. The blue curve shows the actual spectral flux that we measure with satellites at the top of the atmosphere. And the black symbols here, for example, here, tell you which of the greenhouse gases is primarily responsible for the difference between the black-body emissions that you would get from the surface and what you actually observe at the top of the atmosphere.

So notice that there aren't very many parts of this longwave part of the spectrum which are close to their black-body curve, and an awful lot of absorption occurs. But there's this nice window here between wave numbers of about 800 and about 1,000 inverse centimeters, which is an atmospheric window where a lot of the infrared radiation coming from the surface does go directly to space. There's a big gap here caused mostly by carbon dioxide. Carbon dioxide is very active in this range of wave numbers and blocks a lot of the infrared radiation from going directly to space from the surface in this range of wave numbers or wavelengths.

Water vapor is active in several parts of the spectrum here to the left at relatively high wavelengths, or low wave numbers. But also much of the infrared radiation out here in the shortwave end of the infrared spectrum is taken out by water vapor. Methane is active here, nitrous oxide, and so forth, and even there's an ozone curve. So to actually calculate the spectra exactly we have to take into account the often complex, but well-understood and well-calculated absorption and emission spectra of various greenhouse gases in our atmosphere.

Let's wrap this up by looking at a summary of radiation transmitted by the atmosphere given in this diagram. Let's first focus at the top part of this diagram, which, once again, shows the black-body curves for the Sun. In this case, it's assigned the value of 5,525 degrees Kelvin.

So this red curve here is the black-body curve for the Sun. And in here are three black-body curves representative of the Earth corresponding to temperatures ranging from 210 Kelvin to 310. 210 is the temperature representative of the upper troposphere. 310 is about as hot as it ever gets at the surface. So over on the left, the shaded red region represents the part of the solar spectrum that's transmitted down to the surface on average.

Now, what we see here is hardly any of the ultraviolet part of the spectrum, the part that's shorter than visible wavelengths gets transmitted to the surface. And in fact, the absorption, percent absorption is given by this second panel in this graph. Almost all 100% of the ultraviolet light is taken out. This turns out to be by absorption and photodissociation of ultraviolet due to ozone principally in the Earth's stratosphere. Without the ozone layer, a lot of this ultraviolet radiation would come down to the surface. And we would be in deep trouble, if that were the case, because ultraviolet radiation is very bad for life, as anybody who's ever had a serious sunburn can attest.

On the other hand, a great deal of radiation in the visible part of the spectrum does make it through. This is kind of a gap where there's very little absorption by gases in the atmosphere of the radiation. Undoubtedly, that is why our human eyes have evolved to see in the visible. That's a part of the spectrum that makes it through the atmosphere with very little distortion allowing us to see relatively long distances.

There are in the longwave side of the solar part of the spectrum some nice gaps corresponding to higher absorptions. These are due to various greenhouse gases, principally water vapor. We'll come back and talk about which gases are doing this absorption and emission in a moment.

Now, over on the terrestrial side of the spectrum, we see a different picture, very little of the infrared radiation emitted by the surface actually gets out directly. There are huge gaps in here. And the percentage of radiation transmitted through the atmosphere is given, again, by this second panel. There is a gap here, a window in the middle of the terrestrial spectrum, where radiation does get through. But over on the shortwave side of the terrestrial spectrum, almost all the radiation is absorbed somewhere in the atmosphere before being re-emitted. And likewise, in the longest wave part of the spectrum, most of the radiation is absorbed before being emitted.

Now, what's doing this absorption is given by the lowest panel on this diagram. Water vapor as given here is responsible for a lot of the direct absorption of solar radiation by the atmosphere in this range. And also a lot of the absorption of terrestrial radiation trying to go out. The carbon dioxide bands are here. Here, where there is not much terrestrial or solar radiation, and a little bit over on the longwave side of the solar spectrum.

Ozone is principally active in the ultraviolet part of the spectrum here. And then, we have other absorption bands due to methane, nitrous oxide. At the very bottom here, we have the Rayleigh scattering curve, which operates mostly in the shortwave side of the solar spectrum.

Now that we have some understanding of how radiation is transmitted through our atmosphere, let's go back to basics and talk about the mean surface temperature we would have in the absence of greenhouse gases, simply as a way of seeing how important greenhouse gases really are in our atmosphere. And we'll also talk about the atmospheres of other planets.

So this is an equation that we talked about earlier in the course. Using the Stefan-Boltzmann law to define something called the mean emission temperature. So Stefan-Boltzmann law says that the amount of radiation emitted by the surface of a planet is the Stefan-Boltzmann constant sigma times its temperature to the fourth power. In equilibrium, this has to equal the amount of radiation absorbed by the surface, which, as we've seen before, is a solar constant divided by 4 times 1 minus the planetary albedo, which is simply the scattering, the back scattering of radiation integrated over all wavelengths and averaged over time for the planet.

Let's look at the effective emission temperatures of three planets Venus, the Earth, and Mars in the order of their distance from the Sun. So we look at this, the solar intensity at the radius of Venus' orbit is about 2,600 watts per meter squared, whereas Earth, which is further from the Sun is only a little bit more than half of that at 1,350 watts per meter squared. And Mars is less than half of that, that's 600 watts per meter squared.

On the other hand, Venus has a very high albedo, because of the clouds and haze in its atmosphere. Earth has somewhat lower albedo of about 33%. And Mars is even darker with a mean albedo only a little bit more than half that of Earth.

And so if we look at the effective emission temperature, curiously enough, it's lower for Venus than for Earth, even though Venus is much closer to the Sun. Because of its high albedo, it's reflecting a lot of that sunlight back to space. So if we calculate the mean emission temperature, it's 240 degrees Kelvin. And the Earth's mean temperature is 251. And Mars' mean temperature is much lower at 216. So of the three planets, Earth, curiously enough, has the highest effective emission temperature.

But let's look at the observed temperatures. The Earth's mean surface temperature is close to about 295 degrees Kelvin. Mars is well below freezing at 240. But Venus is 700 Kelvin. Why is that?

Well, that's simply because Venus has a huge amount of the greenhouse gas carbon dioxide in it. Venus likely suffered a runaway greenhouse effect some time ago, which eliminated liquid water, which is the main sink for carbon in the atmosphere. In a runaway greenhouse effect we have lots and lots, and lots of CO2 in the Venus atmosphere. And that's why its surface temperature is almost unimaginably hot.