In applying the concepts we've just learned about radiation to the real world, it proves very helpful to talk about a concept called radiative equilibrium. Radiative equilibrium is simply the equilibrium state that the atmosphere would achieve in the absence of all kinds of energy fluxes, except radiative fluxes. So in this state, each sample of air is in local radiative equilibrium in the sense that it's absorbing just as much energy as it's emitting.

One thing that is conceptually useful about radiative equilibrium is that it is the state, broadly speaking, to which radiative heating or cooling drives the actual state of the atmosphere. So knowing the radiative equilibrium state gives one some idea of the state to which radiation is trying to drive the actual atmosphere. Now, we're going to skip from these very simple models to a full up calculation of radiative equilibrium in the atmosphere.

This was a calculation that was first done in the 1960s. And in this particular calculation, we are specifying at their climatological values the vertical distribution of all the radiatively important trace gases-- carbon dioxide, methane, ozone, and water vapor. We're going to see later in the course that specifying the water vapor distribution is a bit of a cheat in this calculation, because it's convection that actually is responsible for this distribution of water.

And the convection is largely driven by radiation. So in fact, it should be a two-way calculation. But for the purposes of illustration here, we're simply going to specify the vertical distribution of water and calculate the radiative equilibrium. So here it is. This is temperature in Kelvin as a function of altitude in kilometers, or if you prefer, pressure in millibars on the left hand axis.

And in this calculation, the surface temperature is 333 degrees Kelvin, which is very, very hot indeed, much hotter than we observe over most of the surface of the Earth, decreasing upward very rapidly to very low temperatures at pressures of perhaps 200 millibars or an altitude of 10 kilometers. These temperatures can be as low as 190 degrees Kelvin, which is somewhat colder than we observe the real tropopause to be.

Then the temperature increases upward and is fairly constant in the lower part of the stratosphere, increasing with height. So here is an example of a calculation of radiative equilibrium in which radiation is the only mechanism by which energy flows from one layer of the atmosphere to another. If we compare that to the observed structure of the atmosphere, if we compare that to the observed temperature profile of the atmosphere, we see some interesting similarities and differences.

Just as in the radiative equilibrium calculation in the Earth troposphere, temperature decreases with altitude. But somewhat more gently. Surface temperatures average about 15 degrees C, about 288 degrees Kelvin, not 333 Kelvin. They reach a minimum of around minus 60 degrees, 213 Kelvin, not 190 Kelvin. So the tropopause is somewhat warmer.

But the stratosphere is actually quite similar to the radiative calculation we showed you. In fact, the Earth's stratosphere is not in most places all that far away from what one would calculate from pure radiative equilibrium. Another interesting point is to consider how long it takes an atmosphere of a given state to relax to a state of radiative equilibrium.

So we're going to take the same model of the atmosphere, and we're going to start it with a vertically uniform temperature of zero degrees centigrade, and calculate the time tendency of temperature from the radiative imbalance at each level of the model. And so what this graph shows is, temperature is a function of height. And each of these different color curves represents a different time in the calculation, from its initialization at day zero, all the way through day 10.

So one can see that after 10 days, clearly, the atmospheric temperature profile is still evolving. It takes a long time in our atmosphere for radiative equilibrium to be achieved. In this graph, we're going to start with day 10. We're going to start where the other graph left off and go all the way to day 150.

And one can see that between day 10 and day 25, the troposphere of this model has pretty much reached equilibrium. So in this calculation, it takes a few tens of days for the troposphere to come into a state of radiative equilibrium.

But the stratosphere up above 250 millibars here, this part of the atmosphere, is still quite clearly involving even toward the end of this calculation. So it takes an order of 100 days or so for the stratosphere to come into equilibrium from an isothermal initial state. So one of the key conclusions we can reach from these calculations is that radiation is a relatively slow process in the atmosphere.

It takes tens or hundreds of days for an atmosphere out of equilibrium to come into radiative equilibrium. And the fact that these time scales are long will prove to be important, as we'll see later in the course. With models, we can do other experiments to illustrate the importance of various different radiatively active trace gases.

So the black curve in this diagram shows a variation on this radiative equilibrium called radiative convective equilibrium. We'll be talking about that later in the course. But the other colored curves on this diagram show radiative convective equilibrium in certain experiments in which we've selectively removed one kind of radiatiely active trace gas or another.

So for example, let's look at this green curve here. This is where we've taken out all the ozone. And you can see that having done so, we have a slight cooling of the troposphere, fairly uniform up to the tropopause, but a profound cooling of the stratosphere. In the next slide, we're going to blow up the stratosphere and look at this in more detail.

But ozone is singularly responsible for the fact that temperature actually increases with altitude in the stratosphere. This is a direct result of the absorption of ultraviolet radiation by ozone in the atmosphere, which we talked about earlier in the course. Now let's look at the red curve. The red curve leaves the ozone in but takes carbon dioxide out.

So we're going to take out carbon dioxide all together. And we go from a surface temperature of about 30 degrees in this calculation to a surface temperature of about 20 degrees. We're leaving the water vapor in, though. We're not allowing that to respond to the cooling.

So this does not include things like water vapor feedback, this kind of calculation. Not only is the surface colder, but the whole troppsphere is colder. Remarkably, however, taking out the carbon dioxide leads to a warming of the stratosphere. We'll come back and talk about that in a minute.

Finally, we're going to take out water vapor and leave the other trace gases in. Taking out all the water vapor reduces the surface temperature from 30 degrees centigrade to zero degrees centigrade. This again illustrates that, because of its abundance primarily, water vapor is the most important greenhouse gas in the atmosphere.

But it doesn't do much in the stratosphere. Now, this is the same set of calculations, but I'm showing you only really the stratosphere and the upper part of the troposphere. So rather than to graph the results as I did in the previous graph, as a function of pressure, I'm going to show you the results as a function of the base 10 logarithm of the pressure.

So this is 100 millibars here, 1,000 millibars at the bottom, 10 millibars up here. And the tropopause varies, of course, depending on the calculation but it's in the lower half of this diagram. So here one again can see that taking out the water vapor doesn't have much effect on stratospheric temperatures. That's simply because there's hardly any water vapor in the stratosphere.

Taking out ozone has the profound effect of cooling the stratosphere, and the temperature decreases upward in the stratosphere without ozone. Instead, if we take out carbon dioxide, we actually get a warmer stratosphere. Why's that? Well, it turns out that the radiative balance in the stratosphere is mostly one between absorption of ultraviolet radiation directly from the sun by ozone, which drives the temperature up to quite large values, and emission of infrared radiation, mostly by carbon dioxide, because there's not much water in the stratosphere.

So the fundamental role of carbon dioxide in the stratosphere is as an infrared emitter. Taking it out means that the atmosphere has to get much hotter to radiate the same amount of energy to balance absorbion of ultraviolet radiation by ozone. That's why taking out carbon dioxide actually leads to a warming of the stratosphere.

This is an important point, because if we add carbon dioxide to the atmosphere, as clearly we are doing, we're going to have the opposite effect. We're actually going to cool the stratosphere. And that's one of the surefire fingerprints that manmade global warming is actually happening, because we observe that the stratosphere is actually cooling.

If the world were warming up for another reason, for example, because of increased solar radiation, then we would see the stratosphere warming up, just as the lower part of the atmosphere warms up. So we'll return, again, to this full calculation of radiative equilibrium, with a very hot surface temperature, very cold tropopause temperature, and a fairly constant temperature in the lower stratosphere increasing upward. As I mentioned before, this is fairly close to the observed conditions in the stratosphere but not so close in the troposphere.

What's the problem with the solution in the troposphere? Well, it's too hot at and near the surface. It's too cold at and near the tropopause. Therefore, the lapse rate of temperature in the troposphere is too large.

But on the other hand, the stratospheric temperature is close to observed. How can we explain the departures of the real climate state from radiative equilibrium? That will be the subject of the next section of this course.