In the last video, we saw that the radiative equilibrium of a troposphere is unstable to convection. We showed that by demonstrating that when the entropy decreases with altitude, as it does in the radiative equilibrium solution, the atmosphere is unstable to convection. And that convection will quickly render the atmosphere nearly neutral to convection, which means that the entropy profile would be constant with height.

Now, this brings us to the subject of radiative convective equilibrium. This is what happens when both radiation and convection are active and establish a new equilibrium. This equilibrium is different qualitatively from radiative equilibrium in that it is a statistical equilibrium state.

Convection itself is chaotic. That is convection is very time-dependent. It varies a lot in a space, like boiling water. But if we take an average over many convective plumes or over much time, we can derive a state which is statistically stable which we call radiative convective equilibrium.

Now, the easiest way to calculate that is simply to assume that what the convection does is render the atmosphere neutral to itself, that is render the atmosphere as having a constant entropy profile. And so whenever we find in a radiative equilibrium state that the entropy actually decreases with height, we adjust the entropy profile back to constant while conserving energy. This is the simplest way of estimating the radiative convective equilibrium state.

Now, here is a diagram that shows what that adjustment actually does. So what you see here is the original radiative equilibrium profile, this profile here. And the profile, once it's been adjusted-- that's this profile here-- this represents constant entropy, which means that the temperature lapse rate is g over cp, about 1 degree per 100 meters. Let's compare these two profiles.

Remember that the pure radiative equilibrium had a very high surface temperature of 333 degrees Kelvin, of course, much higher than observed anywhere on the planet. But the adjusted state is much cooler at the surface, although still much warmer than observed with a surface temperature of about 318 Kelvin. Note that the profile of temperature in the adjusted state, here, obeys the constant entropy lapse rate of about a degree per 100 meters.

So you'll notice that this adjusted state is much warmer through much of the troposphere except very close to the surface where it's cooler. You might also notice the profiles are slightly different even in the stratosphere. Now, why should that be so?

After all, the stratosphere, unlike the troposphere, the radiative equilibrium state is actually stable to convection. So why do we see any difference? This is a reminder that radiative transfer is non-local, that is if one changes the temperature or emissivity of any part of the atmosphere, that changes the radiation emitted from that layer.

And that, in turn, will change the radiation absorbed by other layers. So whenever one makes an adjustment to one part of the atmosphere, potentially, any other part of the atmosphere can adjust. And we see that in this adjusted profile.

Now, although the radiative convective equilibrium solution is much closer to what we observe in the atmosphere than the pure radiative equilibrium, it still has some problems. It's still too hot at the surface and too cold at the tropopause. Why is that?

Well, it turns out that the reason for this, for the most part, is that in the real atmosphere, convection involves a phase change of water. And whenever water changes phase in convection in the atmosphere, we call that kind of convection moist convection. Now, here is a photograph I once took from an airplane showing a typical cloudscape in the tropical atmosphere.

It's really quite beautiful. What one sees is this collection of cumulus clouds-- here's one, for example-- ranging in size some very small fractus clouds, like this guy, to trade cumulus clouds, like this one. And in the distance, one sees a very large cumulonimbus cloud going all the way up to the tropopause.

Several things to note about this. First of all, what is a cloud? A cloud is simply a very dense collection of very tiny condensed water droplets or ice crystals depending on the temperature. They're so small that their terminal velocities are tiny compared to air motions. And we can consider the water to be in suspension.

Now, condensed water forms in the atmosphere, generally speaking, when samples of air expand and cool, their saturation vapor pressure drops down to below the actual vapor pressure of the sample, water vapor condenses and forms a cloud. This happens most commonly when air rises from high pressure near the surface towards lower pressure higher in the atmosphere. It expands and cools. And we'll talk a little bit about how that happens in a moment. But for now, just think of these cumulus clouds as representing places where air is on the whole ascending.

When water vapor condenses in the atmosphere, it releases the latent heat of vaporization. When it freezes, it also releases the latent heat of fusion. So air ascending in these clouds is not cooling at the adiabatic lapse rate we defined before. Therefore, our whole idea of convective adjustment has to be altered to account for this heat released when water vapor condenses.

Another thing to notice about this state is that, very typically, the updrafts, as denoted by the clouds, cover a relatively small fractional area of the sky, that is there is somewhat more clear air than there are clouds in a scene like this. This scenario that you see in this photograph is very much what we would expect to see in an atmosphere that was in radiative moist convective equilibrium where the two main heat transfer processes are radiation and moist convection.

Moist convection extends from a few hundred meters above the ocean surface, sometimes higher above the land surface, in some cases like this cloud in the background all the way up to the tropopause. Below the bases of the clouds, very frequently, the atmosphere is undergoing dry convection, that is without a phase change of water. Let's talk a little bit about moist convection.

The important properties of moist convection, so far as they affect the equilibrium state, is, as I mentioned before, significant heating owing to the phase change of water. This phase change, by the way, can and does operate in both directions. Water condenses in the atmosphere. Condensed water also evaporates, in many cases, absorbing the latent heat of vaporization or fusion and causing the air cool.

The other important aspect of moist convection is that it redistributes from its source at the surface water up through the atmosphere. It is because of moist convection that our atmosphere itself is moist. Convection is the agent of lofting water.

But water vapor, as we've seen before, is the most important greenhouse gas in the atmosphere. So the moist convective radiative equilibrium is strongly interactive. The instability of the radiative equilibrium drives moist convection. The moist convection lofts water from its source at the surface and controls the water vapor content of the atmosphere, which, in turn, determines to a large degree the radiative transfer. The other important aspect of moist convection is that by lofting water, it indirectly contributes to stratiform cloudiness, that is layered clouds, which have a large effect both on shortwave and longwave radiative transfer.

Let's review, to begin with, the essential characteristics of water as a substance. This is a diagram showing the phase equilibrium of water as a function of temperature. And that phase equilibrium is denoted here by the equilibrium saturation vapor pressure.

So there are three phases represented on this diagram, ice, liquid, and vapor. All of these three phases co-exist at something called the triple point. All these phases are in equilibrium with each other. This occurs at a temperature near zero degrees C and a vapor pressure of a little bit over 6 hectopascals.

This curve is the phase equilibrium between liquid water and vapor. Notice that it increases toward the right as one increases the temperature, the vapor pressure increases. And it does so according to something called the Clausius-Clapeyron equation, which is a very important relationship in atmospheric science. So as one increases temperature, the saturation vapor pressure increases. It turns out it increases exponentially.

Now, beyond something called the critical point here, it's no longer possible to distinguish between the vapor and the liquid phase of water. We don't need to worry about that in our atmosphere, because that critical point occurs at a temperature above 600 degrees Kelvin. Now, this curve here represents the phase equilibrium between liquid and ice.

It occurs at a temperature of zero degrees at the triple point. But that temperature actually declines as pressure goes up. That means that as one applies pressure to water ice, eventually one can melt it under pressure. This is a somewhat peculiar characteristic of water as a substance. Other substances have phase equilibria between their liquid and solid phases which increase as one increases the temperature.

Now, the third equilibrium, according to the Clausius-Clapeyron equation is the equilibrium between water ice, and vapor. And this starts at the triple point and goes down as the temperature decreases. So like the vapor-liquid equilibria, the saturation vapor pressure over ice increases with temperature.

Now, one thing that you'll notice on this diagram is the dashed line which is a continuation of the liquid vapor equilibrium to temperatures below the critical point. This represents, once again, the equilibrium between the vapor and liquid phases. But we've carried that equilibrium below freezing.

We've done so, because it turns out-- and we'll talk about this later-- there can be a great deal of supercooled water in the atmosphere, that is liquid water droplets that exists at temperatures below freezing. And the fact that these two curves are different, that is the vapor ice equilibrium differs from the vapor liquid equilibrium, turns out to be important for the physics of clouds.