To recap from the last video, this diagram shows the various phase equilibria among the three phases of water-- vapor, liquid, and ice phase. These phase equilibria are determined by something called the Clausius-Clapeyron equation. Generally speaking, for example, if one raises the temperature, the vapor pressure of water vapor in equilibrium with a plane surface of liquid water goes up, tends to go up somewhat exponentially.

Now, what are the consequences of this for our atmosphere and our climate? Now, the first question we might ask is, what happens when saturation actually occurs? We might be tempted to think that when saturation occurs, well, water condenses into liquid or solid phase.

But in fact, this would not happen if it turned out that our atmosphere was completely clean. That is, it was devoid of small, pre-existing liquid or solid particles that we call aerosols. If the atmosphere had no aerosols, one would need very large supersaturations for condensation to occur in the atmosphere.

But in fact, the nucleation of liquid or solid phase water takes place in the atmosphere through a process called heterogeneous nucleation. This is the condensation of vapor onto preexisting solid or liquid particles called aerosols. And because our atmosphere has plenty of aerosols, we can virtually take for granted that when nominal saturation is reached-- that is, saturation with respect to a plane surface of liquid water-- water vapor will condense.

This is called heterogeneous nucleation, again, and it requires supersaturations that are measured in tenths of a percent or less. So for all practical purposes, we can consider the tiny suspended droplets of water that have condensed on the aerosols, or ice, to be in thermodynamic equilibrium with their environment. And this is an important simplification in atmospheric thermodynamics. So supersaturations in practice are very small in our atmosphere.

Now, it will become important when we talk about how rain and snow are formed. To think about the sizes of these droplets that result from water vapor condensing onto aerosols, as you might imagine, at least initially, the size distribution-- that is, the probability distribution of drop sizes-- is sensitive to the size distribution of the aerosol particles that serve as condensation nuclei. That subset of aerosols that are particularly attractive for the condensation of water are called cloud condensation nuclei, as stated here.

Now, condensation is fast. And this is a wonderful illustration, in fact. This is just a photograph of a jet fighter flying at high speed. In the reference frame of the fighter, air is, of course, flowing from right to left in this diagram-- very fast.

And as the air encounters the aircraft, and its lifting surfaces and so forth, it forms a series of pressure waves, which, if the jet is flying at supersonic velocity, can take the form of shock waves. Now, these pressure waves cause adiabatic expansion and compression of the air. This big white cap that you see in the back here is a region of very low pressure. Air moving through that region expands adiabatically, and saturation vapor pressure, which is just a function of temperature-- drops. And in this case, it's dropped down to below the actual vapor pressure of the air, so the air become saturated with water, and the water condenses.

Well, it doesn't take a lot of imagination to see that in this case, the time scale of air to pass through this pressure wave is really, really small-- much less than a second-- and that's quite enough time for the water to condense. So we don't need to worry in practice about how long it takes for water vapor to condense onto aerosols. We can simply assume that as soon as nominal saturation is reached, the water vapor will condense.

Now, on the other hand, if we ask, how does the water actually fall out of the atmosphere once it's condensed, we get into some very interesting and thorny questions. The droplets that typically form from condensation are so small that their terminal velocities are tiny. In particular, they're much smaller than air motions. So we consider those drops, or ice crystals, to be in suspension.

Even if we allow condensation to continue through the whole depth of the troposphere, by condensation alone, we cannot make these drops or ice crystals large enough to fall at appreciable velocity. So for many decades, the whole notion of how you get condensed water from the form of tiny, suspended particles into actual raindrops or snowflakes or hailstones or other large particles that fall at appreciable velocity has been a challenge in atmospheric science. Now, it was thought through the 1950s that the primary way this works is through something called the Bergeron-Findeisen Process. And this relies on the existence of supercooled water in clouds.

So let's go back to our phase equilibrium diagram here. Now supposing we have a cloud that's formed of liquid water particles, but exists at temperatures below freezing. So supposing that we have particles in this regime here. And so, super cooled water exists at temperatures below freezing, but it is otherwise in thermodynamic equilibrium with the atmosphere.

Now supposing that higher in the cloud, there are ice particles that fall into this region here. Those ice particles, as you can see from this diagram, will be supersaturated with respect to the ice vapor equilibrium-- this curve here-- whereas the water cloud, of course, is in thermodynamic equilibrium along this Clausius-Clapeyron relationship here. So any ice particle falling into supercooled water cloud will find itself supersaturated with respect to ice.

And what happens then is there's a rapid deposition of the water vapor onto the ice crystal at the expense of the liquid drops. And that ice crystal can grow very rapidly. This, in fact, is the basis for a kind of weather modification we call cloud seeding where we look for supercooled water clouds, and we drop into them small particles that act as very good freezing nuclei.

The interesting thing about our atmosphere is although condensation nuclei are very plentiful, ice nuclei are not so plentiful, and that's why we find clouds that have supercooled water. So by artificially introducing particles that have molecular structures similar to that of water ice, we can induce the rapid deposition of vapor onto those molecules, and as it were, create snow, which of course, under the right conditions, will melt as it falls down, and become raindrops. But this process can happen naturally when ice falls into a supercooled water cloud.

For some period of years, cloud physicists thought of this was the primary way that we could get clouds to precipitate. And although this is certainly a way to do it, there are other ways. The other way that is very active-- particularly in warm clouds-- we refer to as stochastic coalescence. And this is simply a term describing what happens when small water droplets or ice crystals that are in suspension collide with each other, and merge, and create over a period of time droplets that are fast enough to fall at appreciable velocity.

Now, this process turns out to be very sensitive to the drop size distributions. That is, in an extreme case, if all the suspended cloud water drops are the same size, and they're falling at the same terminal velocity, the chances they will collide with each other are not so great. And the chances, even if they do collide with each other, that they'll merge-- as opposed to just bounce off of each other-- are also not all that great.

On the other hand, if we have a very broad distribution of drop sizes, this process can operate very efficiently, as the larger particles will sweep through the smaller particles, and collect them via collision. The bottom line is that this stochastic coalescence process is a strongly non-linear function of the cloud water concentration, but it is also a function of the drop size distribution. So clouds that don't have very much liquid water in them will, generally speaking, never precipitate over their lifetimes, particularly if they have a very narrow drop size distribution.

So if you look out the window on a sunny summer day, and you look at fair weather clouds-- cumulus humilis-- there's certainly condensed water in those clouds, but at nowhere near the concentrations that are necessary for stochastic coalescence. These clouds will never develop rain over their lifetime, as you probably know intuitively. On the other hand, very tall cumulus clouds-- cumulonimbus clouds-- do produce rain because of their high water concentrations.

Another important point about the formation of precipitation is that it takes time. Unlike condensation, which is virtually instantaneous, it may take half an hour for even a tall cloud to develop precipitation. And once again, this is sensitive to the initial distribution of droplets.

Take an interesting example, clouds that form in the interior of continents in the summer have very plentiful condensation nuclei, because of all the suspended dust and so forth in the atmosphere. And those nuclei tend to have fairly peaked drop size distributions, so the drops in the clouds will have fairly peaked distributions. It's very hard for them to form precipitation, so it takes a very tall, dense cloud in the interior of the continent to rain, all other things being equal.

At the other extreme might be a relatively small cumulus cloud in some part of the world which is relatively clean. That is, where the aerosol concentration is low, such as Hawaii, in the middle of the Pacific Ocean. Not only are the aerosol concentrations low, but they tend to have quite broad distributions of size. For example, there are giant sea salt particles that can act as condensation nuclei.

As a consequence of this broad distribution of aerosols, it doesn't take much of a cloud to rain in Hawaii. So a tourist on vacation in Hawaii from Colorado may be surprised by quite a wet rain shower coming from a cloud that would never rain in Colorado. Now that we know something about how water changes phase in the atmosphere, and how precipitation is formed, we're in a position to talk about the stability of the atmosphere to moist processes. This will be the subject of the next video.