Let's now talk about feedbacks in the climate system. We'll begin by showing some examples of feedbacks.

Water vapor is perhaps the most important feedback that we know about in the climate system. Water vapor is mostly just a function of temperature in the atmosphere, but water vapor is an important greenhouse gas. So when one increases the temperature, water vapor is thought to increase the feedback through the infrared part of the spectrum when the temperature is positive. That increases the temperature further, which increases the water vapor content further. That's an example of a probably positive feedback in the system.

Ice albedo is another positive feedback in the system. Ice is very reflective. Ice in the net cools the planet because of its high albedo. If the climate were to warm and the ice were to melt, ice would be replaced by water or land surface. That would decrease the albedo, leading to a further warming-- another example of a positive feedback.

Clouds also have large effects on climate, as we've seen before. Because they're highly reflective in the short wave, they exert a cooling influence on the climate. But they are also very effective greenhouse agents, and that provides a positive forcing.

So cloud radiative forcing can be of either sign. The feedback effects of clouds, of course, depend upon how they change in response to other climate forcings. And then on longer time scales, there are various biogeochemical feedbacks that affect, for example, the greenhouse gas composition of the atmosphere.

Well, let's look at some more quantitative estimates of climate sensitivity. We'll go back to the equation that we developed earlier in this part of the course for climate sensitivity-- lambda sub R, just the rate of change of surface temperature with the radiative forcing, Q.

And that can be expressed as the climate sensitivity S in the absence of feedbacks, divided by a factor 1 minus S times the sum of the various feedbacks. Now remember, S is defined as really the rate of change of surface temperature with net radiative forcing in the absence of feedbacks.

Now, let's take a simple kind of calculation where we assume that the surface temperature is simply proportional to the effective emission temperature of the planet, which is specified by the solar irradiance and the albedo. And suppose that the short-wave radiation is insensitive to the surface temperature.

So we would have that the net infrared flux at the top of the atmosphere, here, is proportional to minus the Stefan Boltzmann constant times the effective emission temperature, raised to the fourth power. Therefore, its derivative with respect to surface temperature-- which again, we hold as proportional to the effective emission temperature-- is just d by dT of sigma T e to the fourth, which is minus 4 sigma T e cubed.

But we know what the Stephan Boltzmann constant is, and the effective emission temperature of the planet, about 255 Kelvin-- so this works out to be just shy of four watts per meter squared per Kelvin. The climate sensitivity in the absence of feedbacks is the inverse of that, about a quarter of a Kelvin meter squared per watt.

Using this magnitude of S, we can now estimate the magnitude of various feedbacks in the climate system. Experiments with one-dimensional radiative convective models, such as the ones that you were using in connection with this class, suggested a good first approximation is to assume that the relative humidity is fixed, so that the total water concentration is just a function of temperature.

When we do that, we find that the product of the derivative of the outgoing infrared radiation with respect to water vapor, and the derivative of the water vapor concentration with respect to surface temperature-- holding relative humidity fixed-- is on the order of two watts per meter squared per Kelvin. Which, when multiplied by the feedback-free climate sensitivity parameter S, gives a non-dimensional number of about 0.5.

Now, remember that the net climate sensitivity is equal to S over 1 minus the sums of these factors. So if the only feedback operating were water vapor feedback, since 1 over 1 minus 0.5 is equal to 2, that would imply that water vapor by itself doubles climate sensitivity.

But if you add in other positive feedbacks, as we saw and kept emphasizing earlier, the feedback effects don't add linearly. The effect of water vapor on the sensitivity would be even larger.

Another important feedback in the system is the ice albedo feedback. And this is operative even on the time scale of a year or so. And we can see this very clearly in the annual range of albedo. So this presents estimates of the annual range of albedo in percent in both the northern and southern hemispheres, the northern hemisphere given by this curve with the open circles, and the southern hemisphere by this curve with the closed circles.

Of course there's hardly any ice albedo in the equatorial regions, but there's a little bit owing to mountain glaciers. But we see very large variations in middle and high latitudes, as snow and ice advance and retreat with the seasons.

Now, when we look at this in a longer time scale using something called energy balance climate models, we see that the ice albedo effect can potentially cause very large variations in climate, and leads almost certainly to multiple equilibria in the climate system-- that is, situations where for a given solar constant and atmospheric composition, we can have more than one stable equilibrium.

What this graph shows is the result of running such an energy balance climate model into equilibrium, with various kinds of radiative forcing. So we can think of the radiative forcing as being either the effective solar flux, here expressed as fractions of today's solar irradiance-- so 1 is today's solar irradiance, 0.9 would be 90% of that, and so forth-- or as the logarithm of the partial pressure of CO_2 in the atmosphere, which can be read off the bottom axis here.

The quantity that's being graphed here, shown on the y-axis, is the limiting latitude of ice. So there's assumed to be ice poleward of this latitude, but not equatorward of that latitude.

So how do we read this graph? Well there are three stable branches in these solutions-- an ice-covered branch down here, an ice-free branch up here, and an intermediate branch here, given by the solid black lines.

So how do we think of this? So supposing the solar flux were only 90% of today's value. But with today's value of CO_2, we would be down in this regime, and the only stable solution to the Earth's climate would be ice all the way down to the equator.

At the opposite extreme, if we increase sunlight a lot, or put lots and lots of CO_2 in the atmosphere, we'd be up in this regime in the upper right, where the only stable solution is a planet which had no ice whatsoever. In between, we have this regime, which is where we are today, where as you decrease the carbon dioxide content or the solar constant, ice advances from high to low latitudes until you get to this tipping point-- when the ice reaches 30 degrees latitude or so-- where you would jump right down to the ice-covered branch.

Likewise, if you were to try to warm the climate, the ice would retreat until it got to somewhere over 60 degrees north, and then jump all the way back to this ice-free branch. This jumping behavior is due to the enormous positive feedback of ice. If you melt too much ice, you start decreasing the albedo so much, the positive feedback runs away until all the ice has melted.

Conversely, if you're down here in this regime, if you get down to 30 degrees, the ice albedo feedback-- again positive-- is such that any further increase in ice cover leads to so much cooling of the planet, through the albedo effect, that you jump all the way down to an ice-covered earth.

So we can use this to estimate how the climate would vary if, for example, we had a very slow-- order of a million-year scale-- variation in sunlight, or maybe carbon dioxide content. So if we start down here with the ice-covered planet, and we increase CO_2 or increase sunlight, we stay on this ice-covered branch until we get to a tipping point. When the sunlight is so large-- or there's so much greenhouse effect from carbon dioxide-- that the ice begins to melt, and a positive feedback of the albedo is so powerful-- in that case, that you would jump quite quickly up to the state where the Earth is completely free of ice.

In other words, the ice melting would expose more land and ocean, would lower albedo, would absorb more sunlight, giving further warming, and so on, until you got rid of the ice. Now, if at this point we started to decrease the solar constant or the CO_2 content, we would remain ice free until we got down to about present values. And then we would jump down to this state here where there is ice down to about 70 degrees latitude or so.

Any further diminishment of the solar constant or carbon dioxide content would slowly bring us down this branch, where the ice advanced equatorward, again until we reached about 30 degrees, when it would jump down. So this ice albedo positive feedback introduces strong hysteresis into the climate system, which is accompanied by multiple equilibrium states.

Let's conclude by talking about feedbacks as they're actually calculated in today's climate models. This graph shows the feedback factor in watts per meter squared per degree Centigrade, calculated from the output of the last two generations of climate models. So each one of these open circles represents a different climate model. And the red dot and blue dot, which we'll focus on here, represent the mean over the most recent generation of climate models-- the so-called CMIP 5 models-- and the generation previous to that, called the CMIP 3 climate models. By the way, there is no such thing as CMIP 4 climate models. So we just changed the convention in how we name the models.

On the bottom axis, we see the type of feedback. The leftmost dot is basically just the Planck function, the temperature itself. And we don't consider that a feedback in this. And that's the ultimate stabilizer.

Heating up a planet causes it to radiate more, which cools it back down.

Now let's look at the various feedbacks, which here have been lumped into water vapor, WV, lapse rate feedback [LR]-- as you change the temperature, the rate of change of temperature in the troposphere with altitude changes. That's a feedback factor. The sum of the two, which we'll focus on here, cloud feedback, C, and the surface albedo feedback, A, and then the net feedback, the sum of all of them, is given in the right-hand part of this diagram.

So the scatter among the different models tells you something about the inherent uncertainty in the feedback parameters. Different models produce different feedback parameters. But on the other hand, the means haven't changed all that much between the last generation of climate models-- the blue dots-- and the current generation-- the red dots.

So you see there's a strong positive water vapor feedback, a negative lapse rate feedback, and the sum of those two is not so uncertain, at least as measured by the scatter among climate models. And it has a magnitude of about 1 watt per meter squared per degree Centigrade.

The cloud feedbacks are much more uncertain. And although most of them are positive, there are a few negative ones in there. The CMIP 5 mean is weakly positive. Surface albedo tends to be a weak positive feedback, and when you put it all together, you get the scatter of model results you see on the right-- with a slightly less positive, or less sensitive, feedback in the most recent generation of climate models compared to the generation before that.

Now we'll end with this graph, which shows again the various contributions of various feedbacks to various models. The different models are listed on the x-axis, stratified by the net change in surface temperature for a doubling of CO_2. So the quantity graphed on this axis is the net change of temperature we get from doubling CO_2.

The dark blue is just the Planck response-- sigma t to the fourth. That's pretty well known, and that's just about the same for all models. As we indicated before, adding in water vapor just about doubles the climate sensitivity, just adding in water vapor by itself. Adding in surface albedo gives you the yellow contribution here. And finally, adding cloud feedbacks gives you these bars here.

So the range of just over two degrees to somewhat over four degrees-- you can see that that variation is dominated by different feedbacks from the clouds. So it is widely regarded that clouds are the largest source of uncertainty in projections made using climate models. And that will serve as a transition into the next part of the course, which explicitly deals with global climate models.