The particular kind of instability that plagues the radiative convective equilibrium solution of our idealized planet is called baroclinic instability. And let's talk a little bit about how that works. So I want to show you two altitudes in the middle latitude atmosphere. The surface down here, and the tropopause up here. And to makes things simple, I'll draw on this diagram a single isotherm separating cold air from warm air in both cases, OK?

And of course, the real world is more complicated. You have a gradual temperature gradient. You don't have just one isotherm separating discontinuously cold and warm air, but just for simplicity, we'll talk about it that way. Now, normally these contours are oriented east-west, but I'm going to perturb them in the particular way that's shown here, so that you have a region of particularly cold air at a particular latitude here at high altitude, and likewise, at the surface, OK? And a region of particularly warm air here at the tropopause and here at the surface.

Now, when we perturb the system away from equilibrium, if you make a cold perturbation, that cold air tends to sink, and air converges into the region of sinking, and spins up by Coriolis accelerations so that, in the Northern hemisphere-- and this diagram pertains to the Northern hemisphere, by the way-- we see that cold air at the tropopause will start to rotate counterclockwise. Likewise, as shown by the purple arrow, warm air will begin to rotate clockwise. Now, the opposite is true at the surface. If you create a cold perturbation at the surface, it tends to spread out and start to rotate clockwise, as given by these purple arrows. Likewise, warm air starts to rotate counterclockwise.

Now, in this particular configuration, let's look at what happens. The warm air's rotating counterclockwise. That circulation extends up to the tropopause and drags this colder air further south, thereby amplifying the initial cold perturbation.

Likewise, the counterclockwise flow associated with the cold air at the tropopause, extending down to the surface, drags this warm air up toward higher latitudes at the surface, thereby exaggerating or amplifying the temperature perturbation at the surface. So these interactions between temperature perturbations near the tropopause and near the surface make the atmosphere unstable. And it turns out that there's a very beautiful body of mathematical theory and simulations with computer models, all kinds of evidence, that show this is a very powerful and pervasive kind of instability that one expects to see in middle and high latitudes under these circumstances. This instability gives rise to the baroclinic cyclones and anticyclones, AKA, low-pressure systems and high-pressure systems, that are so important to the climate of middle and high latitudes.

Here is what a baroclinic cyclone looks like in a satellite picture. This is a cyclone off the East coast of the United States. And of course, what you're seeing in the satellite imagery are clouds. Here are low clouds of the Eastern seaboard of the US. Here are some thunderstorms here. And then this is a region of heavy precipitation.

The actual center of the cyclone is probably located about here. And in a cyclone, the warm air tends to be at and to the east of the cyclone center, and tends to be rising. That rising air cools adiabatically. Water vapor condenses into clouds.

Over on the west side of the cyclone, air is sinking. It's drying out, so you tend to have dry, clear air. Except, you see a lot of clouds in this case in this region here. These are low clouds that form when very cold air from the continent spills out over the warm water of the Gulf Stream, gets heated and moistened from below, you get all kinds of low clouds.

So weather is complex, but this is an example of what an extra-tropical, or baroclinic cyclone looks like from space. It doesn't look very much like a hurricane, which is much more circularly symmetric. That's a different phenomenon altogether. But here is a baroclinic cyclone as seen from satellite.

Now, the high- and low-pressure systems, or cyclones and anticyclones are important to the climate system in many ways. Probably, most importantly, in that they flux energy from low to high latitudes. Let's see how that happens.

Well, let's revert to the diagram that we were just looking at. We saw that, in this case, the circulations that are generated at the tropopause extending down to the surface tend to advect, or transport, warm air northward in the Northern hemisphere, cold air southward, OK? This means that you have a correlation between the North-South component of the wind and temperature. This is also true for moisture, by the way.

And that correlation is such that, in the zonal average, in the net, you have warm air moving poleward, cold air moving equator-ward that tends to warm up high latitudes, and cool down low latitudes. So warm, moist air moves poleward, cold, dry air moves equator-ward. We can formalize that mathematically, and that's what shown in this slide here.

Let's go back to our net energy balance that we derived earlier in this series of lectures, which says that the net convergence of the flux of energy by the atmospheric flow, V, must balance the net radiative convergence into the column. Again, this term here will be 0, if the surface itself is in energy equilibrium. So this is the net radiative flux at the top of the atmosphere, solar minus infrared flux. If that's nonzero, we have to have a convergence of the flow of energy in the atmosphere.

Now, let's break down this flow, density times velocity, into two components. A component indicated by these angle brackets, which is the East-West average over the whole planet at that latitude of the flow, plus a departure from that indicated by the primes. And we'll do the same thing for energy, which is a scalar. We'll denote the energy by its zonal mean. That's given, again, by the angle brackets plus a perturbation.

Now, what is the zonal mean? So any quantity, X, subject to this angle bracket operator is just 1 over 2 pi times the integral over all longitudes, that is, 0 to 2 pi of X. It's just the longitudinal mean value of that. So the primes are the departures from the longitudinal average. The angle brackets are the longitudinal average.

And we can take these two, breakdown, substitute them in. That is, take their product, and then average that over longitude, and this is the equation that we get as a result shown here at the bottom. So it's now the divergence of two terms. One is the product of the means. That is, the zonally-averaged air motion, times the zonally-averaged energy.

And the other is the mean of the product of the departures from the zonal mean. Now, these are called the eddy components. That is, the V prime is the local motion relative to a zonal mean. E prime is the perturbation of energy from a zonal mean. And remember that the over-bar indicates a vertical average which we had to start with, OK?

So this first term here is called the eddy flux. And it occurs when there is a correlation, a nonzero correlation, between, in this case, energy and velocity. This is the mean flux. It's the flux by the mean flow. By the way, the other cross-terms you get when you multiply E times rho V go away when you take the average. So for example, rho V average times E prime, if you take the average of that, by definition, the average of E prime is 0, so there's no contribution from that term. So you really only get two terms here.

Now in the tropics, it's this term, the time-mean fluxes, that do most of the work. So for example, in the Hadley circulation, we have a time-mean, zonal-mean flow toward the south at low altitudes, where the mean energy tends to be small. And we have a positive, or northward, flow at higher altitudes, where the energy tends to be large. This gives a positive vertical average contribution from this, which shows that the Hadley circulation is transporting energy away from the equator.

This term tends to be much smaller in middle and high latitudes, but this term does the work. This is because, in baroclinic eddies, where the air is flowing toward the north, that is, E prime is positive, in the northern hemisphere, the air tends to have higher energy content. It's warmer and moister, and so this correlation is positive.

Whereas, where you have air flowing southward, V prime is negative. The air tends to be cold and dry, so E prime is also negative. And once again, that correlation is positive. So this is how eddies in middle and high latitudes do the work of transporting energy away from the equator.

So let's summarize where we're at. The beautiful nonlinear equilibrium solution that we have for the climate is unstable in middle and high latitudes to eddies. These eddies take energy from the subtropics and transport it up toward the poles. That tends to warm the atmosphere near the poles, and cool it down in the subtropics, thereby upsetting the radiative convective equilibrium. That results in a net inward radiative flux at the top of the atmosphere in the subtopics, to compensate for the eddies taking energy out of the subtropics, and a net outgoing radiative flux at the top of the atmosphere in higher latitudes to compensate for the heat being deposited by the eddies.

Here's a diagram that shows, in this case, from a model, rather than from the real atmosphere, the eddy heat fluxes as a function of latitude and altitude, averaged over a year. So this diagram, in this case, goes from the southern hemisphere on the right-hand side, to the northern hemisphere on the left-hand side. Positive values mean toward the left, or toward the north. This is pressure, which, remember, is a surrogate for altitude.

The tropopause is typically in this region here. So when we look at these eddy fluxes, we see that there are strong eddy fluxes through both the troposphere and the stratosphere, primarily at middle and high latitudes. Sort of maximizing around 50 degrees or 60 degrees latitude, each hemisphere. Very little flux in the topics and the subtopics. That's where the Hadley circulation is transporting a lot of energy and that does not show up in this calculation of eddy fluxes.

In the vertical, there tend to be two peaks in the fluxes. One is very close to, but not quite at, the surface. The top of the atmospheric boundary layer. And the other is near the tropopause. There are strong fluxes there as well.

For other reasons, there tend to be strong fluxes in the stratosphere.