Now we're going to talk about what causes the circulation of the atmosphere and the ocean. We'll start with the atmosphere. Much of the non-convective motion of the atmosphere can be grouped into two categories. The first is large scale quasi-steady overturning motion in the tropics that we've referred to as the Hadley circulation. This is roughly steady in time and doesn't vary that much in longitude, although there are exceptions to that.

But outside the tropics, the circulation is dominated by eddies, whose horizontal dimensions are typically 3,000 kilometers or so. How should we consider these circulations? And how should we think about how they arise?

A very nice thought experiment that helps us answer these questions is to consider, first, a hypothetical planet that's very much like the Earth, but doesn't have any continents, and doesn't have any seasonal variation in solar radiation. We're going to make one other approximation to this idealized planet, which is that the only friction acting in the atmosphere is between the atmosphere and the surface. So there's only surface friction. We'll ignore frictional dissipation that's internal to the atmosphere.

Now it turns out that this hypothetical earth-like planet has an exact, non-linear equilibrium solution for the flow of the atmosphere. That is, we can solve all of the equations and get a nice, exact solution. This solution is quite simple. It's characterized by every individual column of the atmosphere being in a state of radiative-convective equilibrium, which we've already talked about extensively.

So we're just going to calculate this radiative-convective equilibrium at each latitude. We don't have to have calculate it at each longitude because, in this hypothetical planet, there are no variations in longitude. And that will be the temperature of the system. Simple.

We're also going to require that the wind vanish at the planet's surface. So there'll be no surface wind. Now if we do that, of course, we're going to find that the temperature falls off from the equator toward the poles. And because of that, we'll discover that there have to exist horizontal pressure gradients in the atmosphere. In this hypothetical planet, these pressure gradients are going to be balanced by rotational effects on atmospheric wind. These rotational effects are called *Coriolis accelerations.* So how does this work?

Let's first talk about hydrostatic balance. We've seen this equation before. It simply says that in a resting atmosphere, the rate of change of pressure with altitude is equal to minus the density of the fluid times the acceleration of gravity. So this hypothetical state, because it's not moving in the vertical, will be in hydrostatic balance. We can combine that with the ideal gas law, which relates density to pressure and temperature. With the ideal gas constant given by R. And this tells us that pressure decreases upward more slowly at higher temperature.

So the columns that are near the equator are going to have pressure decreasing upward more slowly than columns at higher latitudes. And let's look at this visually. So here is a cross-section through our hypothetical planet, extending from the equator to, let's say, the North Pole. Of course, the southern hemisphere would be an exact mirror image of this. And in our hypothetical planet, we'll assume that the pressure at the surface is constant. This is important because it means that the air is not going to be moving horizontally at the surface, and therefore, there will be no frictional dissipation according to our idealization.

Now let's look at this hypothetical state in which the atmosphere is in radiative-convective equilibrium at each latitude. And look at the geometry of different pressure surfaces. Let's, for example, take the 800 hectopascal pressure surface, this white line here. And we'll look also at 500 millibars and 200 millibars. And we'll see that these surfaces are tilted downward toward the pole.

This is simply a consequence of hydrostatic equilibrium. The pressure where the air is hot is decreasing upward more slowly than when the air is cold. And so surfaces of constant pressure must tilt downward toward the poles.

Now the problem with this is that air tends to accelerate from high pressure to low pressure. So this would tell us that air should accelerate this way, which would transport heat toward or away from the equator and upset the radiative-convective equilibrium.

Well let's look more carefully at horizontal force balance. First of all, starting with an inertial reference frame. That is, we're going to pretend that our idealized planet isn't rotating at all. And we have equations of motion in the horizontal that are exactly parallel to the equation of motion that we developed in the vertical direction earlier in this course. Except, of course, there's no gravity acting in the horizontal directions.

So Newton's Laws, the equation of motion, are very simple in this reference frame. They say that the acceleration of flow in the eastward direction-- we'll call that component u-- is equal to minus alpha-- which remember is the inverse density-- times the pressure gradient in the x direction. Now, of course, in our idealized planet, we don't have any gradients in the x direction. So this equation would be zero equals zero.

We have an equivalent equation in the y direction. The acceleration of flow in the northward direction, v-- v is the south to north wind component-- is equal minus alpha-- the specific volume or inverse density-- times the pressure gradient in y. Well we've just seen that because of hydrostatics, there will be a pressure gradient in y. Therefore, there should be an acceleration in the north south direction.

So in an inertial frame, air accelerates down the pressure gradient. What would this due to our equilibrium state? Well, generally speaking, we would have an acceleration at higher altitudes, particularly from the equator toward the pole. And we might expect that to drive an overturning circulation that looks like this yellow arrow, with cold air sinking, hot air rising in the equatorial region. And, of course, that circulation would transport energy poleward.

That would tend to warm up air at high latitudes, cool it off at low latitudes, and upset our radiative-convective equilibrium state. So our hypothetical atmosphere won't work if the world is not rotating.