Up until now, we've treated climate as a one-dimensional system dominated by convective and radiative energy transfer. But the real world, as we all know, is three-dimensional and varies in time, as this photograph from space taken in an infrared channel reminds us. The atmosphere and the oceans move, and in so doing, they transport energy, trace gases, aerosols, and so forth.

How does this affect climate? That will be the subject of the section. Let's begin by noting that the overall forcing the system, solar radiation, varies with latitude and time. We've seen this diagram before, in which we have the solar radiative flux at the top of the atmosphere as a function of the time of the year, indicated down on the x-axis, and latitude, from the South Pole to the North Pole.

If we look at the equinoxes-- for example, March 21 here, roughly, and September 21 here-- solar radiation peaks at the equator and falls off gradually away from the equator and more rapidly toward the poles. But during the solstice seasons, for example, the Northern hemisphere summer solstice, the radiative flux at the top of the atmosphere varies just a little between the summer pole and the equator, and actually has an absolute maximum at the summer pole. This is also true, of course, in the Southern hemisphere summer solstice here.

Another way to look at this is to look at the average radiative transfer over a year and compare that to the solstices. This is a diagram showing solar radiative flux at the top of the atmosphere, averaged over a year. This thick black curve shows this, going from the South Pole here to the North Pole here. As we would expect intuitively, the radiative flux reaches a maximum at the equator and falls off toward the poles. Of course, it's not zero at the poles, because the poles receive radiation during six months of the year.

Now, if we look at the two solstice seasons, we see that the radiative flux actually peaks at the poles. Doesn't vary much between the poles and roughly 30 degrees latitude, but then falls off sharply across the equator toward the winter hemisphere.

How does the climate system respond to these latitudinal and time variations of the solar flux? Well, as we reviewed earlier in the course, of course, the surface temperature is a maximum, more or less, where the radiative flux is a maximum in the equatorial regions. But of course it's not quite that simple. We see when we look at this satellite infrared map of ocean temperature that there are interesting variations and departures away from a simple north-south gradient in temperature.

And, of course, this varies in time. This animation shows the variation of the Earth's surface air temperature as a function of month of the year. And as we might expect, it pretty much follows the evolution of the solar flux. The temperature pattern migrates north and south, along with the solar radiative forcing.

Owing to the fact that the Earth's surface temperature varies, for reasons that we're going to explore in this section, the atmosphere and the oceans move. Let's just have a look at some measures of that. This chart shows the January mean surface wind speed and direction. This surface wind has been deduced from a very interesting instrument called a scatterometer, mounted on satellites. This instrument sends pulses of microwave radiation to the sea surface of a wavelength that roughly corresponds to the wavelength of capillary waves on the surface. These are the small ripples that respond instantly to changes in wind. By measuring the return at various angles, one can get a sense of both the amplitude and the orientation of these capillary waves, which are a direct measure of the wind stress at the sea surface.

Knowing the wind stress, one can make a pretty good estimate of the wind speed and direction, and that's what this chart shows, averaged over January. So what do we see? Well, we see a belt of very strong easterlies [winds from the east] in January north of the equator here. We see a region of relatively light winds here, which used to be called the horse latitudes, and a belt of stronger winds in middle latitudes, flowing from west to east. In the Southern hemisphere-- and we see this, really, at all times of the year-- we have a belt of very strong westerlies [winds from the west] blowing over the Southern Ocean. And, again, in the Southern hemisphere, a belt of relatively weak winds.

We do see southeasterly [winds from the southeast] winds south of the equator in both the Atlantic and the Pacific. These easterly winds are part of a circulation that historically has been called the Hadley circulation. These winds are also known as the trade winds because, in the early days of commerce by sail, mariners used these winds to travel westward across the oceans.

So the time mean circulation is often characterized in a simple way like this, showing, again, the easterly winds in the tropics, northeasterly to the north of the equator, southeasterly to the south of the equator, converging at the equator. And as the depiction on the left of this diagram shows, that results in ascent along the equator and air traveling polewards, but only to about 30 degrees latitude or so where it subsides [descends] and returns back. These circulations called Hadley cells, named after George Hadley, a British scientist from the 18th century who first looked at winds recorded by mariners and depicted maps showing these trade wind cells.

Now, poleward of the Hadley cells, we see different kinds of circulations. We typically see westerlies in middle latitudes and at least weak easterlies near the poles. But we're going to emphasize that these time mean circulations outside the tropics are not terribly important. They're not the circulations that do most of the transport. Indeed, the transport is caused mostly by eddies [variable flows that deviate from the time-mean].

And that's shown in this instantaneous surface wind map, again, from a satellite-borne scatterometer. But this is for a particular day. And here the coloring shows the speed of the wind, and these white streaks show the direction of the wind here. So north of the equator, we see fairly constant northeasterly trade winds in this diagram, where south of the equator, we see southeasterlies in the eastern part of the Pacific here, but then we have deviations from that strong westerly flow, for example here.

Outside the tropics, we see that the circulation is dominated by gyres. So, for example, we have a big counterclockwise gyre here and clockwise gyres and so forth. These correspond to the high pressure and low pressure systems one sees on television or newspaper weather maps. These are transient eddies. They move typically eastward across a surface, and it turns out that most of the flux of energy, tracers, and so forth that occurs toward the poles is accomplished outside of the tropics by these eddies and not so much by the time mean circulation. But within the tropics, the time mean circulation can be quite important for these transports.

Let's look at this another way. Here is a depiction-- in this case, from a model-- of instantaneous distribution of surface winds shown by the white and blue shading here and winds near the tropopause at the 250 hectopascal pressure surface denoted by colors. So when we look at the surface winds, we see these broad areas of weak trades. This particular diagram doesn't tell you the direction of the wind. A zone of relative calm-- for example, here-- called the Intertropical Convergence Zone, where it turns out these winds converge.

And we have some interesting features here. For example, this region of very strong winds at the surface, here and here, are two tropical cyclones that happened to exist in these fields at this time. But we see outside the tropics signs of a much larger eddy here in the North Atlantic. This is called a baroclinic cyclone [horizontal temperature variations are important]. These are transient and migratory and, as I mentioned before, do much of the work in transporting energy and other quantities in the poleward direction.

Now, the colors here show the speed of the winds near the tropopause. And you note that the pattern that these winds form is quite different from what one sees at the surface. The strongest winds are organized in remarkably narrow bands, which have come to be known as jet streams and which airliners, for example, try to take advantage of when they're traveling from west to east and try to avoid going the other direction.

So why does the circulation of the atmosphere actually look like this? Let's look at a time depiction of the circulation of the atmosphere as represented in a global computer model. Now, the white shading that you see in this diagram represents the clouds produced by this model. Let's look at how they vary in time.

So this is a sequence over several months showing how these fields evolve. And I want you to focus on what's going on outside the tropics. You see these swirls or eddies are particularly strong over the oceans. These are the mid-latitude baroclinic cyclones that are so important in controlling the transport of energy and other quantities across the surface of the earth. Notice that they have a particular scale. They're usually a few thousand kilometers in diameter. Once again, these correspond to the low pressure and high pressure regions one typically sees on daily weather maps.

Now, to go to the tropics, if you look very carefully at the tropics, you might see that there is a general tendency of clouds-- these are low level clouds-- to be moving from east to west. These are clouds embedded in the trade winds that are part of what we call the Hadley circulation.

The overall impression one gets in looking at an animation like this is that the flow of the atmosphere is, in a macroscopic sense, quite turbulent. This turbulence is critically important for climate, controlling the distribution of temperature, water vapor, clouds, and so forth.

And later, we'll talk about how these eddies arise and why they're important.