In this section of the course, we'll talk in more detail about radiative transfer through our atmosphere and its importance for climate. We'll talk about absorption of solar, or shortwave, radiation by clouds, water vapor, ozone, and to some extent, carbon dioxide in our atmosphere. We'll talk about scattering and reflection of shortwave radiation by clouds and surface in the atmosphere. And we'll deal with the absorption and re-emission of longwave radiation by clouds, water vapor, carbon dioxide, methane, and nitrous oxide.

We're going to begin by detailed discussion of the idealization of black-body radiation. And talk about the interaction of radiation with gases, such as greenhouse gases in our atmosphere. And also, towards the end of the section, talk about the interaction of radiation with clouds and aerosols.

Let's begin with a few definitions. We'll begin with something called the radiant intensity, I sub lambda. I sub lambda, as we can see here, is defined as the amount of energy passing through a surface area dA within a solid angle dOmega per wavelength interval per unit time. In MKS, it's expressed in units of joules per meter squared per steradian per meter per second.

So if we have a beam of radiation of radiant intensity I sub lambda in the k-hat direction here, then the amount of energy passing through some area dA is just the projection of I sub lambda on the unit normal vector, normal to the surface on which dA lies. And so the total amount of energy per unit time passing through that area is the radiant intensity times the cosine of the angle theta between vector k and vector n times the area itself times the increment in solid angle Omega times the increment of wavelength.

Correspondingly, we can talk about a quantity called the flux density. The flux density is the normal component of intensity integrated over all solid angles. So we take I of lambda, multiply it by the angle between the n and k vectors, the cosine of that angle, cosine theta, integrate over all solid angles to get something called the flux density.

If we integrate the flux density over all wavelengths, we get the flux per unit area, F. And if we integrate that over the area, we get the total flux, little f. So we'll have occasion to refer to flux intensity, flux density, total flux density, and total flux through this section of the course.

Now let's talk about the idealization of black-body radiation. Black-body radiation is the radiant intensity one would observe under ideal conditions of local thermodynamic equilibrium. This turns out to be an excellent approximation for the emission, absorption, and radiation by our atmosphere, except, perhaps, at very high altitudes. Black-body radiation follows something called Planck's law.

So Planck's law is a law for B sub lambda, that's the black-body radiant intensity I sub lambda for the ideal case of a black body. It's a function of temperature and wavelength. And it's equal to twice Planck's constant h times the speed of light squared divided by the wavelength radius to the fifth power times e to the hc, where, again, h is Planck's constant, c is the speed of light, divided by lambda kt, where k is Boltzmann's constant, and then subtract 1 from that.

What does this curve actually look like? Well, here are black-body curves corresponding to bodies whose effective emissions temperatures range from 5,000 degrees Kelvin, which is close to that of the Sun, down to 4,000 degrees and 3,000 degrees. So when we look at Planck's curve, we see immediately that the total amount of radiant energy decreases quite rapidly as the temperature decreases, and the wavelength here at which the radiation peaks becomes longer and longer, as the body becomes cooler and cooler.

Now, on this diagram, I've put in the background the colors corresponding to the visible range of the spectrum here. This shows that Sun, whose temperature is a little bit higher than 5,000 degrees Kelvin, has peak radiant energy right in the middle of the visible bend. This is perhaps not an accident; our eyes, no doubt, evolved partly to see in that range, where the Sun's very bright.

Now if one takes derivatives of Planck's law, one can find something called the Wien's displacement law, which governs the wavelength at which the black-body radiation reaches its peak. This is a very simple law that says that that wavelength is simply inversely proportional to absolute temperature T by a constant b. So here lambda max is the wavelength at which black-body radiation is maximum, b is a constant equal to about 2.9 times 10 to the minus third Kelvin meters.

We can see this law in action when we look at a very hot body. So for example, this is a photograph of Pahoehoe lava flowing down a hillside in Hawaii. When we look into the interior of this very hot mass of lava, which may be several thousand degrees Kelvin in temperature, it's radiating yellow on the spectrum. Whereas the lava, which is closer to the surface and is cooled off a bit, is red. And when we get to the older lava in the background, it's cool off enough that most of its emissions are in the infrared part of the spectrum that we can't see, and to our eyes the lava looks black.

Similarly, if we look at an infrared image, a false color infrared image, of a human being, we see variations in the effective emission temperature coming from that person and the clothing he's wearing. So the highest temperatures, of course, are the skin temperature of that person in this false color image yellow. And the clothes he's wearing are, of course, cooler-- the scale you can read off on the right. His sunglasses are a lot cooler. And he's got some cloth draped over his left arm, which has got pretty much the air temperature, and is much cooler than that.

Even the night sky radiates. This is a 9-year average image of something called background cosmic radiation, just radiation coming from outer space, which is literally left over from the Big Bang. In fact, it's one of the primary pieces of evidence in favor of the Big Bang theory-- that our Universe began with a colossal explosion.

Now, let's look at the black-body curves representative of the Sun with a mean emission temperature close to 6,000 degrees Kelvin, and the Earth with much cooler effective emission temperature of around 255 degrees Kelvin. So this diagram has wavelength on its x-axis. Notice that it's logarithmic in wavelength. Wavelengths here are expressed in microns, 10 to the minus 6 meters. And the black-body radiant flux in watts per meter squared per micron wavelength interval is given on the y-axis.

Now, in this case, because the Sun is so much hotter than the Earth and it radiating so much more energy per unit area, I have divided the radiant flux of the Sun by a factor of about 3 million, just to make it more easily comparable to that of the Earth. But, remember, that the Sun, of course, is radiating far more energy per unit area, per unit wavelength interval than the Earth. What we see here is that the Sun's emissions peak in the visible range of the spectrum, 0.7 or 0.8 of a micron, whereas the Earth's peak emissions occur in the infrared part of the spectrum here, of around 15 microns or so.

An important observation from this comparison is that there's hardly any overlap between the solar part of the spectrum and the terrestrial part of the spectrum. This offers us a big simplification that we can treat the terrestrial radiation, in the infrared as a separate stream of radiation from the Sun's radiation in the shorter wavelengths, including visible part of the spectrum. So throughout this course, we're going to use the term "solar radiation" and "shortwave radiation" interchangeably. Likewise, we'll use the terms "terrestrial radiation" and "longwave radiation" interchangeably.

Here is an image from satellites of infrared radiation leaving our planet during the month of April 1985. The scale you see here, at the bottom is in watts per meter squared, with the red colors and violet colors indicating higher levels of radiation. As you might guess, in general, there's more radiation leaving the planet in the tropics where it's warmer.

Notice that there are some places, for example, over the Sahara, where the longwave the emissions reach a maximum. There are also interesting areas, for example, over South America, Equatorial Africa, and Indonesia, with relatively little radiation leaving the planet. These are places where there are high thick clouds produced by thunderstorms. These high thick clouds block infrared radiation trying to leave the surface in the lower parts of the atmosphere, and, indeed, are radiating up to space, that effective emission temperature is close to the temperatures at which they occur, which are around 200 Kelvin, whereas the surface of the Sahara, for example, or the tropical oceans are somewhat closer to 300 degrees Kelvin.

So here are direct evidence of the greenhouse effect, if you will, of high clouds blocking infrared radiation from leaving the planet. These regions in the subtropics, for example, over the Sahara, at this time of year over the Northern Indian Ocean, so forth, are places that are not only more or less free of high clouds, but they're very dry. And so there's not much water vapor-- the most important greenhouse gas in the atmosphere-- and photons are coming from very low in the atmosphere and from the surface itself. So these are kind of the radiator fins of our planet.

This, of course, varies in time. At different seasons, this image will look slightly different. But this shows you a general picture of the way our planet radiates energy back to space.

Another important consequence of the black-body law comes from integrating that law over all wavelengths in the hemisphere. And that gives us something called the Stefan-Boltzmann law. So we're integrating over all wavelengths and all angles in the hemisphere. And this law says that pi times the integral of the black-body function-- it's a function of the frequency of the radiation over all frequencies-- we could have done this with the black body as a function of wavelength integrated over all wavelengths, and got the same answer. And that tells us that the net radiation varies as the fourth power of the temperature times a constant, sigma, called the Stefan-Boltzmann constant, which is made up of other constants, like Boltzmann's constant, Planck's constant, and the speed of light.

This tells us that the hotter a body is, the more energy it radiates away and that that energy radiation goes up very quickly with temperature. Now, let's talk about how this energy varies with wavelength and introduce the notion of spectra. A spectrum that everybody's familiar with is called the continuous spectrum. If we have a white light source here, that is a radiant source, whose energy is independent of wavelength, and we break it down as a function of wavelength and observe it, we get something called continuous spectrum, ranging in the visible from red at the longwave end to blue and violet at the shortwave end.

But if, instead, the energy is coming from a hot gas and we break that down with a prism and observe it, instead of a continuous spectrum, we've yet almost nothing at all, except in discrete bands, which comprise something called an emission line spectrum. This is a consequence of quantum mechanics, which we'll talk about in a few minutes, which says that a hot gas should be emitting in discrete line spectra. Another kind of spectrum we can talk about is to take a white light source, pass the radiation through a cold gas, break that apart, in which case we get something called an absorption line spectrum. So we see the continuous spectrum of the white light source in the background. These black lines are where the gases absorb that radiation in the same discrete intervals as it would have emitted that radiation at the same temperature.