Let's wrap up with a brief discussion of how clouds and aerosols affect the transfer of radiation through the atmosphere. We'll undertake a much deeper discussion of these issues later on in the course. We'll first talk about how principally solar radiation is scattered as it enters the atmosphere. Then we'll talk about the absorption and emission principally of longwave radiation by aerosols and clouds.

Let's begin with a discussion of scattering. Suppose we have a beam of radiation travelling from left to right, and that radiation is assumed to interact with small particles in the atmosphere. We can consider several extreme limits of the size of those particles, one being when the particle is quite small compared to the wavelength of the radiation.

This regime, shown here on the left, is called the Rayleigh Scattering regime, and is particularly effective when the wavelength is not too much larger than the particle. In that case, the fraction of incident radiation that's scattered is the intensity of the incident radiation divided by the fourth power of the wavelength. So we can see that scattering is strongly weighted toward shorter wavelengths of light.

The Rayleigh scattering is symmetric such that the amount of radiation that's back scattered toward the source is equal to the amount of radiation here on the right that's forward scattered away from the source. In contrast, the amount of energy that's scattered at right angles to the incident radiation is half that of the back-scattered or forward-scattered parts of the radiation. The fact that most of the light that's scattered, the incident sunlight that's scattered by air molecules in the atmosphere is weighted towards the short wavelengths is responsible for the fact that the sky is blue.

When we look up at the sky, we see incoming sunlight that's been scattered by air molecules. And the scattering that takes place is mostly of the shortest wavelengths of the light, which our eyes, of course, see as blue. When the sun is setting, particularly, if there's air pollution, so there's a lot of scattering taking place, the path length of photons through the atmosphere is much longer, of course, and so much of the bluish part of the spectrum of light might have been taken out of the sun to leave the sun itself looking orange or even red. So this is also a fundamental reason why sunsets are orange and red.

Now, if we have larger particles, for example, particles of dust, soot, smoke, or sea salt in the atmosphere-- these are generally particles we refer to as aerosols-- with respect to sunlight, they're in the Mie scattering regime, where the wavelength of the light is not very different from the wavelength of the particle. In that case, there's asymmetry, and most of the radiation that's scattered is scattered in the forward direction with less in the backward direction, and less still at right angles to the incident radiation. If the Mie scattering involves yet larger particles, this symmetry is even more profound, but there's less total wavelength dependence of the scattering in this case.

The asymmetry of Mie scattering is why, when we look in the direction of sun that's going through light cloud or fog, or smoke, we tend to see a whitish haze around the sun. This represents the preferential Mie forward scattering. This is also the reason why relatively thick clouds, which have a lot of internal scattering, which isn't terribly wavelength dependent, look white. Most of the sunlight is back scattered in all wavelengths from the cloud, this is why cumulus clouds, which are very heavy water content, look principally white to us.

Let's consider the case of a flat horizontal cloud reflecting sunlight back to space. How much of the sunlight does it reflect? This diagram at the left here shows calculations of cloud albedo, which is the fraction of sunlight reflected back to space by clouds, as a function of the solar zenith angle, which is zero when the sun is straight up, and 90 degrees when the sun is at the horizon. And the total amount of condensed water in the clouds, the so-called liquid water path, which is just the integral of the mass concentration of water over the altitude of the cloud-- notice, that this is on a logarithmic scale.

So as we increase the amount of water in the cloud, not surprisingly, the fraction of sunlight that's reflected increases from 20% or so for very thin clouds up to 90% or so for very thick clouds. As the sun gets closer to the horizon, that is the solar zenith angle increases, a fraction of sunlight that's reflected goes up. So sunlight that's at a very shallow incidence angle to the cloud, more of that is reflected that if the sun is straight up.

Let's talk a little bit now about absorption of sunlight by clouds. Cloud particles, which are small droplets of water in this case, not only reflect and scatter sunlight, they can absorb it. And this shows the percentage of the incoming radiation that's absorbed, again, as a function of the solar zenith angle and the concentration of water in the clouds. Not surprisingly, as one increases the concentration of water, a greater percentage of the incoming sunlight is absorbed. But as the sun get closer to the horizon, a progressively smaller fraction of the incoming sunlight's absorbed by the cloud. But we saw over here on the left correspondingly that a larger fraction of that sunlight is reflected by the cloud.

So let's summarize the cloud and aerosol effects. If we talk about the interaction of sunlight and air molecules, this is governed principally by Rayleigh scattering of the shorter wavelengths, principally the blue and ultraviolet parts of the spectrum, which is the fundamental reason that the sky is blue. Aerosols, particles of dust, soot, smoke, sea salt, and so forth in the atmosphere are mostly in the Mie scattering range, where the wavelength of the sunlight is not very different from the size of the particles.

There's some absorption of the incoming sunlight by aerosols depending on their composition. Cloud droplets, water droplets, and ice crystals are also in the Mie scattering regime and also can absorb some of the incoming sunlight. And raindrops, which are much bigger than cloud droplets and also much larger than the typical wavelengths of solar radiation, are in something called the geometric optics regime, and act more like prisms, which is why you need raindrops to see rainbows.

With this elementary understanding of the physics of radiative transfer under our belts, let's go back to this diagram of the Earth's energy budget and see if we can understand more elements of it. This is the net energy budget of our planet coming from the Fourth Assessment Report of the IPCC.

Averaged over a year and averaged over the whole planet, we have 342 watts per meter squared of solar radiation entering the atmosphere, of which 77 watts per meter squared is reflected by clouds and aerosols in the atmosphere, and another 30 watts per meter squared-- somewhat less-- reflected by the surface, principally by bright surfaces, like deserts and ice-covered continents. 67 watts per meter squared, a not trivial sum at all, is absorbed by greenhouse gases in the atmosphere-- so principally, water vapor, and by clouds, leaving at the end only 168 watts per meter squared, less than half the incoming radiation at the top of the atmosphere to be absorbed by the surface.

Now, how does the surface get rid of this energy? In the long term, the amount of energy leaving the surface must equal the amount coming down. What happens?

Well, according to the Stefan-Boltzmann law, sigma T to the fourth, we have 390 watts per meter squared being directly radiated upward, of which 350 is absorbed somewhere in the atmosphere, and only about 40 watts makes it directly out to space here. On the other hand, 324 watts per meter squared is radiated in the infrared back from the atmosphere to the surface by greenhouse gases and by clouds. So this is a remarkable fact that we've emphasized before in this course that on average the surface gets more radiation from the atmosphere, that is from greenhouse gases, and from clouds, than it gets directly from the sun. By almost a factor of 2.

But there's another means by which the surface can get rid of energy. That's by evaporation. So 78 watts per meter squared is lost by evaporation. When you evaporate water from the surface, the heat of vaporization is supplied from the surface.

And likewise, the evaporation acts to increase the humidity or energy content of the air. And 24 watts per meter squared is directly by conduction, if you will, from the surface to the atmosphere and subsequent convection of that heat away from the surface. So it's a very interesting energy budget.

In the end, the atmosphere, the clouds within it, and to a much lesser extent, the surface directly radiates a net of 235 watts per meter squared back to space in the form of longwave radiation, which is the difference between the incoming sunlight at the top of the atmosphere and that fraction of it that's reflected by the surface and by the atmosphere and the clouds within it. These three components-- the incoming solar radiation, the outgoing solar radiation, and the outgoing longwave radiation can all be measured from satellites.