Clouds can impact the climate system in a variety of ways. We're going to explore an atmosphere where human activities have increased the amount of aerosol particles, but where water vapor remains the same.

First, remember that an increase in aerosols themselves can directly impact climate, through absorption and scattering of solar and terrestrial radiation. This is shown in the left-hand most panel. Aerosols also act as the condensation sites of droplets and ice crystals that form clouds. We now consider what happens to clouds if there are more condensation sites. If there's more aerosol particles, but the same amount of water vapor, a cloud will have smaller, but more numerous, droplets.

A cloud with smaller, but more numerous, droplets tends to be brighter, it has a higher albedo and it scatters more solar radiation into space. This is termed the cloud albedo effect, or the first indirect aerosol effect. This is normally attributed to the work of Twomey.

We can also imagine a cloud that has more, but smaller, droplets. Those droplets don't coalesce, and gravitationally settle as quickly. Thus, a cloud would not precipitate as quickly, drizzle would be suppressed, and the cloud would persist for a longer period of time. This is often called the drizzle suppression effect, or the increased cloud lifetime effect. This is attributed to Albrecht. It is sometimes also called the second indirect aerosol effect.

There are, also, interesting cases where absorbing aerosols are present in the vicinity of clouds. This is sometimes called the cloud burning effect, or the semi-direct effect, and it is attributed to the work of Ackerman. The concept here is that absorbing aerosol will heat the local region around a cloud, and actually cause the cloud to evaporate and dissipate. Unlike the other aerosol effects on clouds that we've discussed, this would actually shorten the lifetime of the cloud. Finally, some aerosols are effective at nucleating ice. This is often called the indirect effect on ice clouds, and we will discuss it further in a latter part of this lecture.

We now consider, in more detail, the comparison of two clouds that form in identical conditions, except aerosol concentration. In one case, the left hand side of this figure, aerosol concentration is low, as was the case in a pre-industrial atmosphere, without anthropogenic emissions. In the second case, at right, aerosol is higher, as it would be in the modern atmosphere.

Clouds with low aerosol concentration, that is to say the left side, or the pre-industrial atmosphere, would have very few, but large droplets. Large droplets do not scatter light very well, and so most of the sun's rays are going to pass through these clouds and reach the surface. In the case of high aerosol concentration, there would be a lot of droplets as a result. And these clouds would have small droplets that effectively scatter radiation. In fact, up to 90% of radiation in the visible part of the spectrum can be reflected back into space. These clouds would, consequently, have a much higher albedo.

One of the more complicated, and thus more poorly understood, indirect effects is the nucleation of ice. Ice is formed on special particles, which are termed ice nuclei. Examples of ice nuclei include mineral dust particles. As was discussed in the aerosol lecture, mineral dust is known to have increased in the atmosphere by about 30% to 50%, due to land use changes attributed to humans.

Lohmann considered the climatic effect of increasing the amount of ice nucleating particles in the atmosphere. Shown here are figures of ice water content, as a function of altitude, denoted by pressure in millibars, versus latitude, where the equator is in the middle, and the poles are on the right and left-hand side.

In the right-most figure,

Lohmann considered a case with no special ice forming particles. In the middle case, 1% of the black carbon aerosol in the system-- black carbon representing about 1% of the total aerosol-- was allowed to be effective ice nuclei. We can see that there are substantial changes in the amount of ice water present in this case.

Finally, we can see the substantial changes attributed to a black carbon content of 10% nucleating ice. That is to say, 10% of 1% of the aerosol are now considered to be effective ice nuclei. And we can see ice clouds forming throughout the depth of the troposphere.

Lohmann went on to consider the short and long wave forcing, in this case, versus the base case, where there was no good ice forming aerosol. The result was on the order of 1 watt per meter squared, which is the same as the entire direct effect of aerosols. This exemplifies the large radiative forcing that a very small part of the aerosol population can have, when it affects cloud formation.

Analogous to a figure shown during the aerosol lecture is a set of model results for magnitude of the aerosol indirect effect, due to anthropogenic aerosol. In this case, all models are considering the first indirect effect, or the cloud albedo effect, the increased brightness of clouds, their ability to scatter radiation back into space.

We should note that the cloud albedo effect, or the first indirect effect-- those two terms being synonymous-- are often considered the only forcing among the aerosol indirect effects. The remainder are normally considered to be feedbacks. We see, here, that models range in magnitude, of the aerosol indirect effect, from a very small amount, approximately 0.25 watts per meter squared, to a large effect, almost 2 watts per meter squared, although they have an average of about 0.75 watts per meter squared.

In all cases, these are negative effects, representing a cooling to the climate system, offsetting some amount of the greenhouse gas warming. We now compare the improvement in our understanding of the aerosol indirect effect since the year 2000. The panel at left represents our understanding of radiative forcing, where each column is a different anthropogenic effect. Note the tropospheric aerosol indirect effect portion of the graph. This term means the cloud albedo effect. This figure was generated for the Intergovernmental Panel on Climate Change Report in the year 2000.

The figure at right is the analogous panel from the Intergovernmental Panel on Climate Change Report in the year 2007. Note the row for the cloud albedo effect. The first thing visible is that, in the year 2000, the cloud albedo effect-- which at that time was called the tropospheric aerosol indirect effect of the first type-- was solely an error bar. That is, there was no actual value placed on it. Instead, the range of estimates was everywhere from 0 to about minus 2 watts per meter squared.

In the year 2007, there is an estimate of approximately negative 0.75 watts per meter squared. But the error bar remains rather large, anywhere from about minus 0.25 to almost 2 watts per meter squared. In all cases, a cooling on the climate system.

When we look at the total net of human activities, which is about plus 1.5 watts per meter squared, we notice that the error bar on this ranges from about 0.5 to about 2.5. This error bar is not our misunderstanding, or lack of understanding, in carbon dioxide or the other greenhouse gases. Instead this error bar is the error bar due to our lack of understanding of the cloud albedo effect, shown here.

We change topics, slightly, to the concept of ice snow and feedbacks. Snow and ice feedbacks are related to clouds because they are the result of precipitation. And these represent one classic example of a feedback, which is typically thought of as a higher temperature in the atmosphere increases the melt rate of precipitation, leading to more rain than snow, and a lower albedo, since ice, itself, reflects a great deal of solar energy back into space.

This figure shows the same vantage point, at a different time period, separated by about five decades, of the Swiss Glacier. We can see, in the older figure, the extent of the glacier, and the lack of the glacier in the warmer current climate. The Intergovernmental Panel on Climate Change estimates that the reduced amount of ice, on the surface of the Earth, has led to a warming of about plus 0.25 watts per meter squared. But this is considered a feedback, and not a forcing.

We return to an albedo figure shown in an earlier lecture, where there was a high albedo for fresh snow. A somewhat lower albedo for ice, and an even lower yet albedo for surfaces such as sand, dry, and wet soils. The concept behind the snow/ice feedback is that the shift of higher albedo regions moves to lower albedo, as the ice and snow are removed from the system.

Another concept that relates to aerosol is that, an increase in albedo can also be seen by a dirtying of snow. For example, increases in black carbon aerosol can coat fresh ice surfaces, thus moving them from the fresh part of the regime, to the older part. The Intergovernmental Panel on Climate Change reports that this has a positive radiative forcing on the order of 0.1 watts per meter squared. Although, they admit that the level of understanding is low.