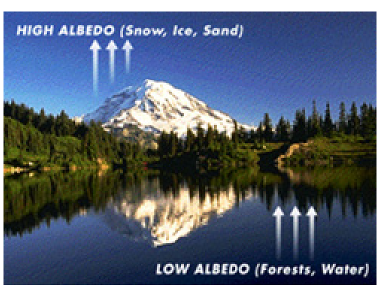
Clouds & Radiation

The study of clouds, where they occur, and their characteristics, play a key role in the understanding of climate change. Low, thick clouds primarily reflect solar radiation and cool the surface of the Earth. High, thin clouds primarily transmit incoming solar radiation; at the same time, they trap some of the outgoing infrared radiation emitted by the Earth and radiate it back downward, thereby warming the surface of the Earth. Whether a given cloud will heat or cool the surface depends on several factors, including the cloud's altitude, its size, and the make-up of the particles that form the cloud. The balance between the cooling and warming actions of clouds is very close although, overall, averaging the effects of all the clouds around the globe, cooling predominates.

The Earth's climate system constantly adjusts in a way that tends toward maintaining a balance between the energy that reaches the Earth from the sun and the energy that goes from Earth back out to space. Scientists refer to this as Earth's "radiation budget." The components of the Earth system that are important to the radiation budget are the planet's surface, atmosphere, and clouds. The energy coming from the sun to the Earth's surface is called solar energy. Most of it is in the form of radiation from the "visible" wavelengths, i.e., those responsible for the light detected by our eyes. Visible radiation and radiation with shorter wavelengths, such as ultraviolet radiation are labeled "shortwave." Both the amount of energy and the wavelengths at which energy is emitted by any system are controlled by the average temperature of the system's radiating surfaces, plus the emission properties. The temperature of the sun's radiating surface, or photosphere, is more than 5500°C (9900°F). However, not all of the sun's energy comes to Earth. The sun's energy is emitted in all directions, with only a small fraction being in the direction of the Earth.



Energy goes back to space from the Earth system in two ways: reflection and emission. Part of the solar energy that comes to Earth is reflected back out to space in the same, short wavelengths in which it came to Earth. The fraction of solar energy that is reflected back to space is called the albedo. Different parts of the Earth have different albedos. For example, ocean surfaces and rain forests have low albedos, which means that they reflect only a small portion of the sun's energy. Deserts, ice, and clouds, however, have high albedos; they reflect a large portion of the sun's energy. Over the whole surface

by Steve Graham
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"The Earth's climate system constantly adjusts"

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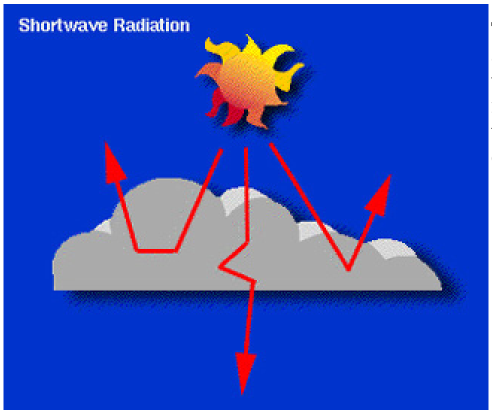
of the Earth, about 30 percent of incoming solar energy is reflected back to space. Because a cloud usually has a higher albedo than the surface beneath it, the cloud reflects more shortwave radiation back to space than the surface would in the absence of the cloud, thus leaving less solar energy available to heat the surface and atmosphere. Hence, this "cloud albedo forcing," taken by itself, tends to cause a cooling or "negative forcing" of the Earth's climate.

Another part of the energy going to space from the Earth is the electromagnetic radiation emitted by the Earth. The solar radiation absorbed by the Earth causes the planet to heat up until it is emitting as much energy back into space as it absorbs from the sun. Because the Earth is absorbing only a tiny fraction of the sun's energy, it remains cooler than the sun, and therefore emits much less radiation. Most of this emitted radiation is at longer wavelengths than solar radiation. Unlike solar radiation, which is mostly at wavelengths visible to the human eye, the Earth's longwave radiation is mostly at infrared wavelengths, which are invisible to the human eye. When a cloud absorbs longwave radiation emitted by the Earth's surface, the cloud reemits a portion of the energy to outer space and a portion back toward the surface. The intensity of the emission from a cloud varies directly as its temperature and also depends upon several other factors, such as the cloud's thickness and the makeup of the particles that form the cloud. The top of the cloud is usually colder than the Earth's surface. Hence, if a cloud is introduced into a previously clear sky, the cold cloud top will reduce the longwave emission to space, and (disregarding the cloud albedo forcing for the moment) energy will be trapped beneath the cloud top. This trapped energy will increase the temperature of the Earth's surface and atmosphere until the longwave emission to space once again balances the incoming absorbed shortwave radiation. This process is called "cloud greenhouse forcing" and, taken by itself, tends to cause a heating or "positive forcing" of the Earth's climate. Usually, the higher a cloud is in the atmosphere, the colder is its upper surface and the greater is its cloud greenhouse forcing.

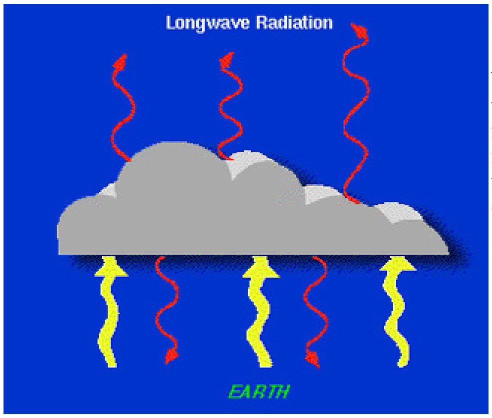
If the Earth had no atmosphere, a surface temperature far below freezing would produce enough emitted radiation to balance the absorbed solar energy. But the atmosphere warms the planet and makes Earth more livable. Clear air is largely transparent to incoming shortwave solar radiation and, hence, transmits it to the Earth's surface. However, a significant fraction of the longwave radiation emitted by the surface is absorbed by trace gases in the air. This heats the air and causes it to radiate energy both out to space and back toward the Earth's surface. The energy emitted back to the surface causes it to heat up more, which then results in greater emission from the surface. This heating effect of air on the surface, called the atmospheric greenhouse effect, is due mainly to water vapor in the air, but also is enhanced by carbon dioxide, methane, and other infrared-absorbing trace gases.

In addition to the warming effect of clear air, clouds in the atmosphere help to moderate the Earth's temperature. The balance of the opposing cloud albedo and cloud greenhouse forcings determines whether a certain cloud type will add to the air's natural warming of the Earth's surface or produce a cooling effect. As explained below, the high thin cirrus clouds tend to enhance the heating effect, and low thick stratocumulus clouds have the opposite effect, while deep convective clouds are neutral. The overall effect of all clouds together is that the Earth's surface is cooler than it would be if the atmosphere had no clouds.

next: cloud forcing



The shortwave rays from the Sun are scattered in a cloud. Many of the rays return to space. The resulting "cloud albedo forcing," taken by itself, tends to cause a cooling of the Earth.



Longwave rays emitted by the Earth are absorbed and reemitted by a cloud, with some rays going to the surface. Thicker arrows indicate more energy. The resulting "cloud greenhouse forcing," taken by itself, tends to cause a warming of the Earth.

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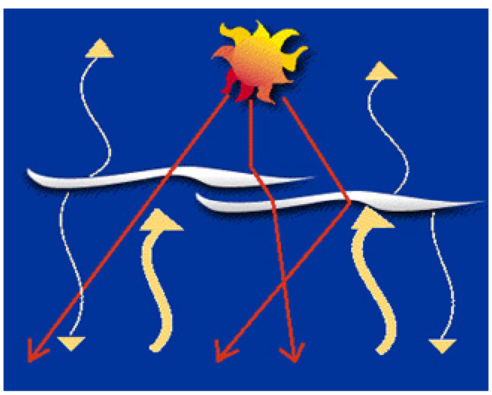
High Clouds



The high, thin cirrus clouds in the Earth's atmosphere act in a way similar to clear air because they are highly transparent to shortwave radiation (their cloud albedo forcing is small), but they readily absorb the outgoing longwave radiation. Like clear air, cirrus clouds absorb the Earth's radiation and then emit longwave, infrared radiation both out to space and back to the Earth's surface. Because cirrus clouds are high, and therefore cold, the energy radiated to outer space is lower than it would be without the cloud (the cloud greenhouse forcing is large). The portion of the radiation thus trapped and sent back to the Earth's surface adds to the shortwave energy from the sun and the longwave energy from the air already reaching the surface. The additional energy causes a warming of the surface and atmosphere. The overall effect of the high thin cirrus clouds then is to enhance atmospheric greenhouse warming.

Image from the Space Shuttle Endeavour on July 1, 1993 (STS-57) showing wispy cirrus clouds.

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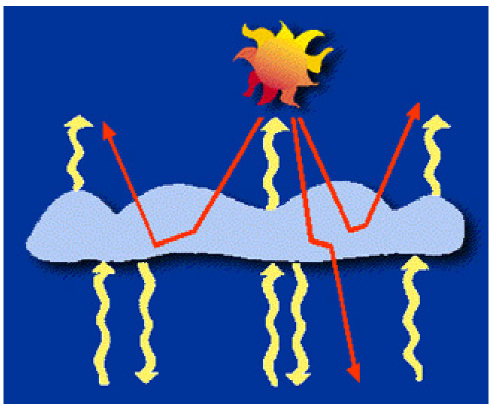
Low Clouds



In contrast to the warming effect of the higher clouds, low stratocumulus clouds act to cool the Earth system. Because lower clouds are much thicker than high cirrus clouds, they are not as transparent: they do not let as much solar energy reach the Earth's surface. Instead, they reflect much of the solar energy back to space (their cloud albedo forcing is large). Although stratocumulus clouds also emit longwave radiation out to space and toward the Earth's surface, they are near the surface and at almost the same temperature as the surface. Thus, they radiate at nearly the same intensity as the surface and do not greatly affect the infrared radiation emitted to space (their cloud greenhouse forcing on a planetary scale is small). On the other hand, the longwave radiation emitted downward from the base of a stratocumulus cloud does tend to warm the surface and the thin layer of air in between, but the preponderant cloud albedo forcing shields the surface from enough solar radiation that the net effect of these clouds is to cool the surface.

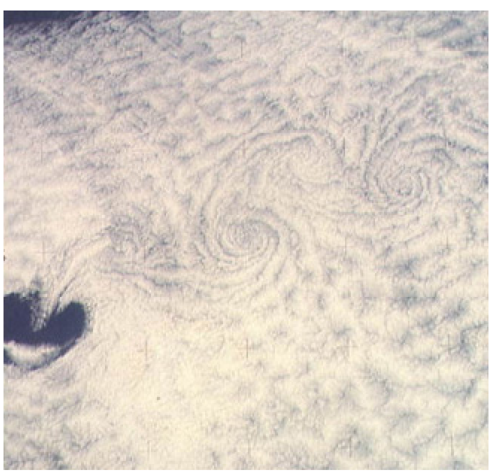


Image from the Second Skylab manned mission on August 1, 1973 showing stratocumulus clouds over the Pacific Ocean.

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Deep Convective Clouds

In contrast to both of the cloud categories previously discussed are deep convective clouds, typified by cumulonimbus clouds. A cumulonimbus cloud can be many kilometers thick, with a base near the Earth's surface and a top frequently reaching an altitude of 10 km (33,000 feet), and sometimes much higher. Because cumulonimbus cloud tops are high and cold, the energy radiated to outer space is lower than it would be without the cloud (the cloud greenhouse forcing is large). But because they also are very thick, they reflect much of the solar energy back to space (their cloud albedo forcing is also large); hence, with the reduced shortwave radiation to be absorbed, there is essentially no excess radiation to be trapped. As a consequence, overall, the cloud greenhouse and albedo forcings almost balance, and the overall effect of cumulonimbus clouds is neutral-neither warming nor cooling.

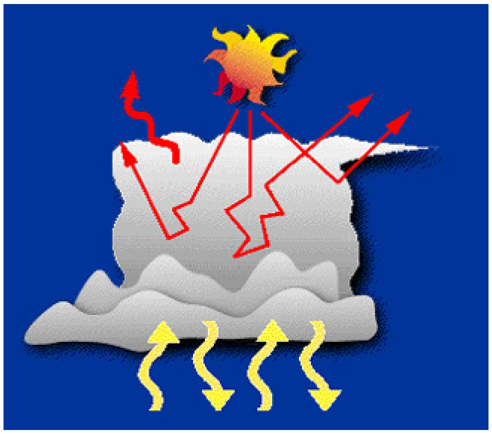

Image from the Space Shuttle Challenger on April 7, 1983 showing cumulonimbus clouds.

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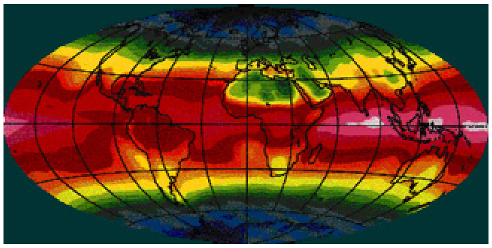
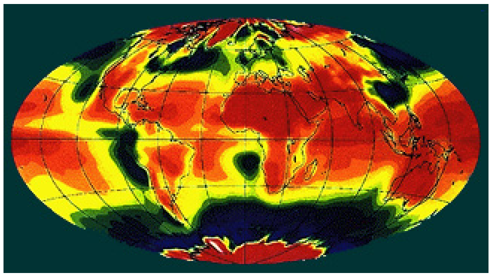
Radiation



Annual average net radiation determined from 1985 to 1986. Net radiation is the difference between incoming solar radiation that is absorbed by Earth and outgoing infrared radiation from Earth that is lost to space. The net radiation is generally positive at low latitudes (increases in heating represented by oranges, reds, and pinks) and negative at high latitudes (increases in cooling represented by greens and blues).



Annual average net cloud radiative forcing (bottom) determined from 1985 to 1986. Net cloud forcing is the result of two opposing effects: (1) greenhouse heating by clouds (or positive forcing)--clouds trap heat coming from Earth's surface that would otherwise be lost to space, and (2) cooling by clouds (or negative forcing)--clouds reflect incoming solar radiation back to space. The relatively large areas where cooling is the greatest are represented by colors that range from yellow to green to blue. In some areas, the effect of the clouds is to produce some warming as shown by colors that range from orange to red to pink. Overall, clouds have the effect of lessening the amount of heating that would otherwise be experienced at Earth's surface (Earth

Radiation Budget Experiment data on the Earth Radiation Budget Satellite and the NOAA-9 satellite. Data processed at NASA Langley Research Center; images produced at the University of Washington).

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