NASA Facts

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The Earth Science Enterprise Series

These articles discuss Earth's many dynamic processes and their interactions

Clouds and the Energy Cycle

The study of clouds, where they occur, and their characteristics, may well be a central key to understanding 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 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. The shortwave reflection by clouds is illustrated in Figure 1.

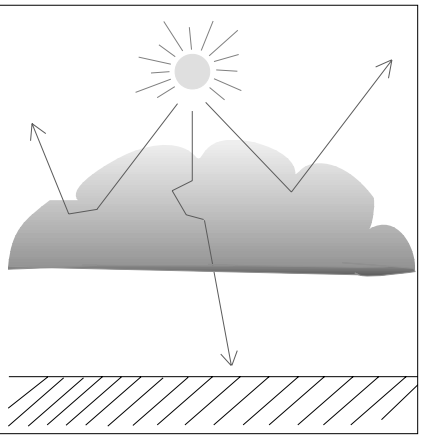

Figure 1. The shortwave rays from the sun are scattered in a cloud. Many of the rays return to space. The resulting "cloud albedo forcing," taken by itself, tends to cause a cooling of the Earth.

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 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 re-emits 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. The absorption and re-emission of longwave radiation by clouds is illustrated in Figure 2.

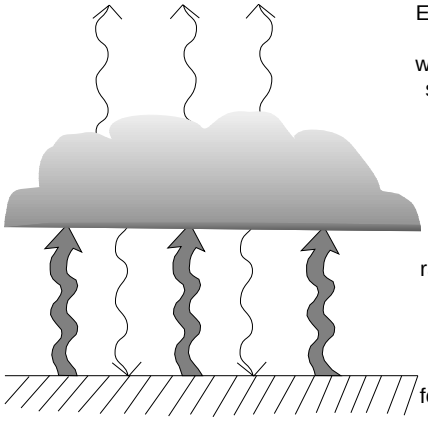

Figure 2. Longwave rays emitted by the Earth are absorbed and reemitted by a cloud, with some rays going to space and some going to the surface. Wavy arrows indicate longwave rays (distinguished from straight arrows, which indicate shortwave rays, as in the previous figure), and thicker arrows indicate more energy. The resulting "cloud greenhouse forcing," taken by itself, tends to cause a warming of the Earth.

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.

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. The effect of cirrus clouds is illustrated in Figure 3.

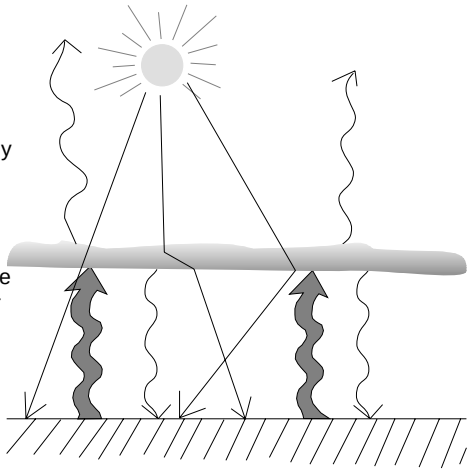

Figure 3. Cirrus clouds transmit most of the incoming shortwave radiation, but they trap some of the outgoing longwave radiation. Their cloud greenhouse forcing is greater than their albedo forcing, resulting in a net warming of the Earth.

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. The effect of stratocumu-

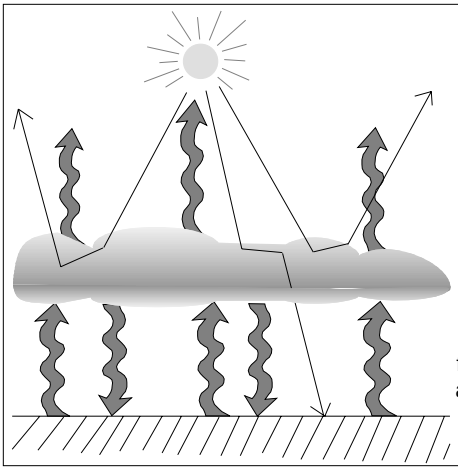

Figure 4. Stratocumulus clouds reflect much of the incoming shortwave radiation but also reemit large amounts of longwave radiation. Their cloud albedo forcing is larger than their cloud greenhouse forcing, resulting in a net cooling of the Earth.

lus clouds is illustrated in Figure 4.

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

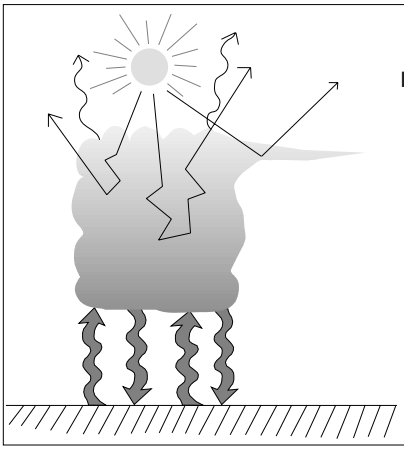

Figure 5. Deep convective clouds emit little longwave radiation at the top but much at the bottom. They also reflect much of the incoming shortwave radiation. Their cloud greenhouse and albedo forcings are both large, but nearly in balance, resulting in neither warming nor cooling.

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. The effect of deep convective clouds is illustrated in Figure 5.

Clouds—A Key Variable in Global Change

- The effect of clouds on climate depends on the competition between the reflection of incoming solar radiation and the absorption of Earth's outgoing infrared radiation.
- Low clouds have a cooling effect because they are optically thick and reflect much of the incoming solar radiation out to space.
- High thin cirrus clouds have a warming effect because they transmit most of the incoming solar radiation while, at the same time, they trap some of the Earth's infrared radiation and radiate it back to the surface.
- Deep convective clouds, on average have neither a warming nor a cooling effect because their cloud greenhouse and albedo forcings, although both large, nearly cancel one another.

NASA Missions to Study Clouds and the Energy Cycle

Studies of clouds and the energy cycle have been performed for many years as part of a number of NASA missions. In the near future, small missions addressing specific investigations are planned, leading up to the main initiative of NASA's Earth Science Program, the Earth Observing System (EOS) series of satellites beginning in 1999. Some of these missions are listed in the accompanying table.

Historically, the Television Infrared Observation Satellite (TIROS) series provided a technology test to obtain daily temperature and global cloud-cover data. The Nimbus series provided the first global radiation budget analysis from space, indicating that the planetary albedo was lower and the outgoing infrared radiation higher than previously believed. The Earth Radiation Budget Experiment (ERBE) provided an improved and more-comprehensive analysis of the global radiation budget and, especially, the first global observations of cloud greenhouse and albedo forcings. The Upper Atmosphere Research Satellite (UARS) monitors the solar energy reaching the Earth and provides data on upper atmospheric chemistry and dynamics. The early Spacelab/Space Transportation System (STS) and the Atmospheric Laboratory for Applications and Science (ATLAS) payloads launched on the Space Shuttle provided data on solar energy, sun-atmosphere interactions, and upper atmospheric chemistry and dynamics.

Pathfinder Data Sets

The Pathfinder Program was initiated by NASA and the National Oceanic and Atmospheric Administration (NOAA) to provide access to large sets of remote-sensing data applicable to global change research in general. Data regarding clouds and the energy cycle are being made available by NASA. Two key sources of Pathfinder data sets are Synchronous Meteorological Satellite/Geostationary Operational Environmental Satellite (SMS/GOES) and NOAA/Advanced Very High Resolution Radiometer (AVHRR) data. These data are valuable in studies of cloud patterns and characteristics over broad spatial (a few kilometers to thousands of kilometers) and temporal (minutes to years) scales.

The Next Steps

An important mission for the study of clouds is the joint U.S./Japan Tropical Rainfall Measuring Mission (TRMM). TRMM, launched in November 1997 carries the EOS Clouds and the Earth's Radiant Energy System (CERES) instrument, an improved version of the ERBE instrumentation. Also, TRMM carries instrumentation to study evaporation of water vapor into the atmosphere and its condensation to produce rainfall, processes of primary importance to the global energy budget. Several of the EOS series of satellites will carry the CERES instrument and other advanced instrumentation to provide a highly-accurate, self-consistent, and long-term (15 years) cloud and radiation data base. Analyses of these data, building on the foundation laid by previous missions, will lead to a better understanding of the role of clouds and the energy cycle in global climate change.

Related NASA Websites

The Earth Observing System Educators' Visual Materials: *http://eospso.gsfc.nasa.gov/eos_edu.pack/toc.html*

Earth Science Enterprise Poster Series: *http://eospso.gsfc.nasa.gov/eos_posters/posters_toc.html*

Goddard Institute for Space Studies: *http://icp.giss.nasa.gov/education/cloudintro/*

Weather and Climate Studies in the 21st Century: *http://www-airs.jpl.nasa.gov/education.html*

Earth Science Enterprise

Selected Missions Studying Clouds and the Energy Cycle

Mission	Launch	Scientific Objective
TIROS series	1960-1965	Technology test of satellite weather system to obtain daily temperature and cloud-cover data
Nimbus series	1964-1978	Cloud-cover data, nighttime infrared data, temperature data, radiative energy balance
SMS/GOES series	1974-	Cloud imagery and temperature and moisture data from geostationary orbit
NOAA-7, -9, -11, -12, -15	1981-	AVHRR cloud imagery and temperature data from polar orbit
Spacelab/STS payloads	1981-1985	Solar UV energy, sun-atmosphere interaction
Earth Radiation Budget Experiment (ERBE)	1984-1986	Monitor shortwave and longwave components of the Earth's radiation budget
Upper Atmosphere Research Satellite (UARS)	1991	Monitor solar energy, upper atmospheric chemistry and dynamics
ATLAS/STS payloads	1992-1994	Monitor solar energy, upper atmospheric chemistry and dynamics
Tropical Rainfall Measuring Mission (TRMM)	1997	Monitor cloud properties and the Earth's radiation budget
Earth Observing System (EOS)	1999-	Comprehensive investigations of cloud properties and the Earth's radiation budget, particularly with data from the EOS AM and PM Missions, beginning in 1999
CloudSat	2003	The first global survey of the synoptic and seasonal variations of cloud and aerosol vertical structure
Picasso-Cena	2003	Provide key measurements of aerosol & cloud properties needed to improve climate predictions