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The Importance of Understanding Clouds

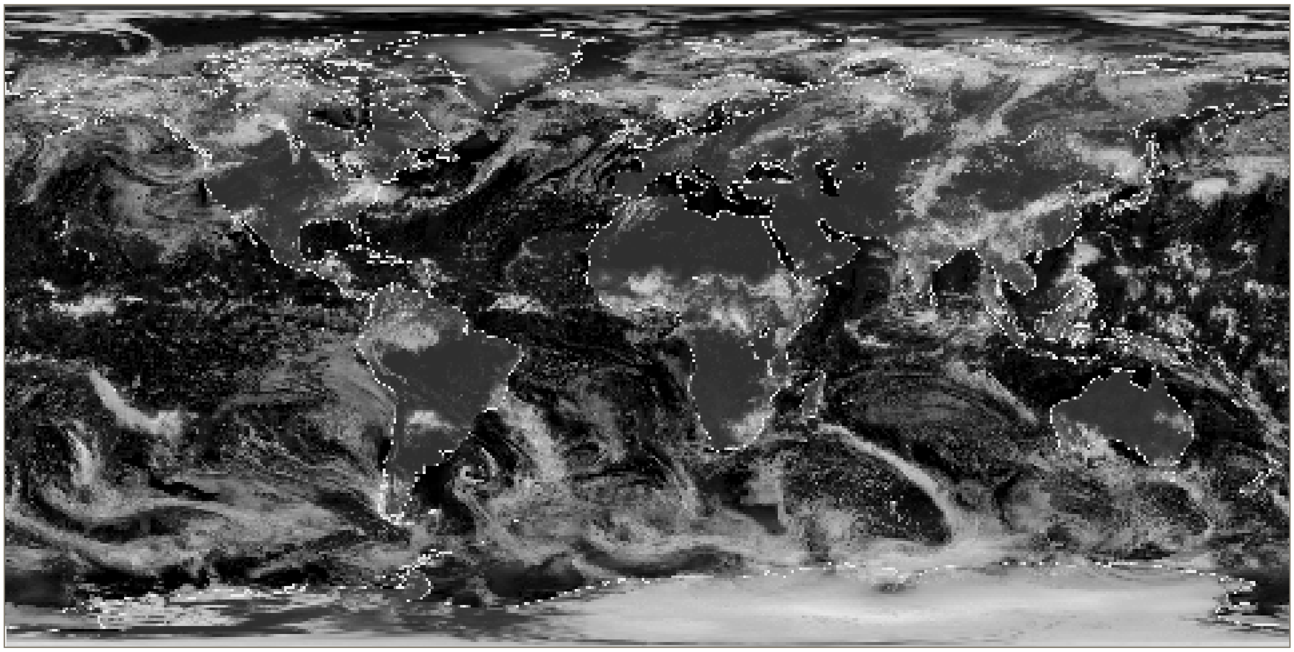
One of the most interesting features of Earth, as seen from space, is the ever-changing distribution of clouds [see **Figure 1**]. They are as natural as anything we encounter in our daily lives. As they float above us, we hardly give their presence a second thought. And yet, clouds have an enormous influence on Earth's energy balance, climate, and weather.

Clouds are the key regulator of the planet's average temperature. Some clouds contribute to cooling because they reflect some of the Sun's energy—called *solar energy* or *shortwave radiation*—back to space. Other clouds contribute to warming because they act like a blanket and trap some of the energy Earth's surface and lower atmosphere emit—called *thermal energy* or *longwave radiation*.

Cloud systems also help spread the Sun's energy evenly over Earth's surface. Storms move across the planet and transport energy from warm areas near the equator to cold areas near the poles. For more details on the topic of Energy Balance, refer to *NASA Facts 2005-9-074-GSFC*.

Even small changes in the abundance or location of clouds could change the climate more than the anticipated changes caused by greenhouse gases, human-produced aerosols, or other factors associated with global change. In order for scientists to create increasingly realistic computer simulations of Earth's current and future climate, they'll have to include more accurate representations of the behavior of clouds. For this reason,

Figure 1. This image gives an idea of the widespread distribution of clouds in Earth's atmosphere and is an example of the unique views of clouds that satellites can provide. Two days of data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra spacecraft were combined to produce this view of clouds over the whole Earth. (Image Credit: Reto Stöckli.)



Clouds

clouds are an important area of study for the Earth-Sun System Division in NASA's Science Mission Directorate.

Recipe for a Cloud

The Right Ingredients

Clouds are collections of tiny particles of water and/or ice that are large enough to be visible. What ingredients are needed to make a cloud? The two required ingredients are *water vapor* and *aerosols*. Water vapor enters the atmosphere through evaporation from open water, the soil, or the leaves of plants. The wind transports water vapor from one region to another through a process called *advection*. Aerosols come from natural sources such as volcanoes or forest fires, as well as from human activities such as air pollution. Some aerosols are *hygroscopic*, meaning they readily absorb and retain water. Hygroscopic aerosols become the core, or nucleus, of cloud droplets [see **Figure 2**], and so scientists call them *cloud condensation nuclei* or *ice nuclei* (*nuclei* is the plural of *nucleus*).

The Right Conditions

Simply having moisture and aerosols present in the atmosphere does not guarantee a cloud will form. To form an analogy to cooking, a bowl of flour, eggs, butter, and sugar will not come together to form a cake unless the ingredients are combined under just the right conditions. What conditions do we need to have present in the atmosphere for clouds to form?

To answer this, we have to understand the concept of stability—a measure of equilibrium illustrated in **Figures 3a** and **3b** with a simple system consisting of marbles and a bowl. **Figure 3a** illustrates the system in *stable equilibrium*. When the marble is disturbed, it may move around for a while, but it quickly settles back to its original position. **Figure 3b** shows the system in *unstable equilibrium*. In this case, if the marble is disturbed, it will continue to move away from its original position.

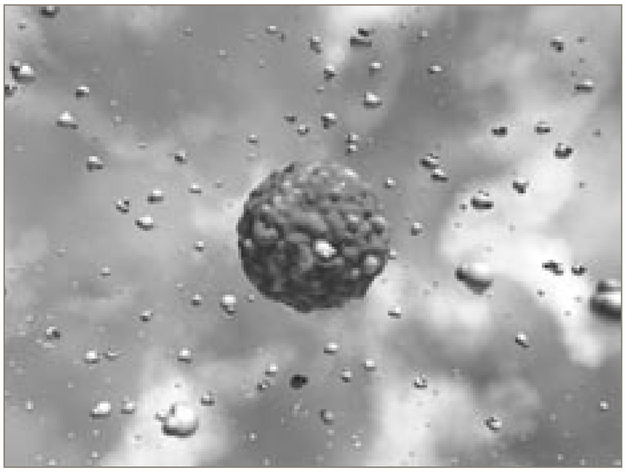
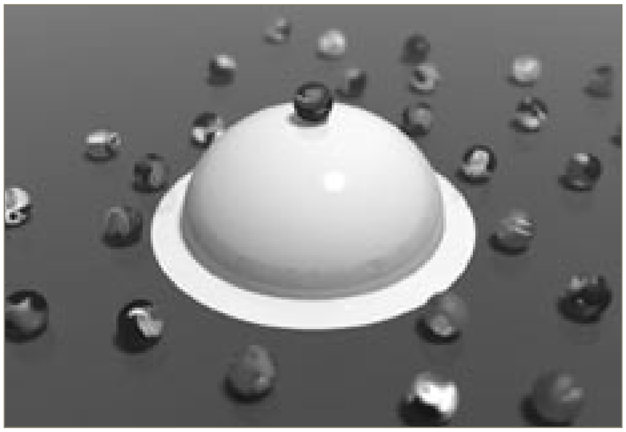


Figure 2. Tiny water droplets begin to cluster around a hygroscopic (water attracting) aerosol and form a cloud droplet. If this process continues long enough, the cloud droplets grow into raindrops. A similar process allows ice crystals to grow. (Image credit: Alex McClung.)



Figures 3a (upper) **and 3b** (lower). The concept of stability can be illustrated using this simple system consisting of a bowl and marbles. **Figure 3a** depicts a stable system. If the marble is given an initial "push" in this environment, it moves for a time, but eventually returns to its initial position. On the other hand, **Figure 3b** shows an unstable system. If the marble is given an initial "push" in this environment, it continues to move. It doesn't return to its initial position. (Image credit: Alex McClung.)

The same idea can be applied to Earth's atmosphere, but it is a little more complicated than the simple system with the marbles. To help us understand stability in Earth's atmosphere, it's helpful to define a *parcel of air*. The parcel is a thin bubble of air that doesn't exchange heat with the surrounding atmosphere so that we have what scientists call an *adiabatic process*. Since no other sources of energy are present, the parcel will expand and cool when it rises, and compress and warm when it lowers.

Like the simple system with the marbles, when the atmosphere is in stable equilibrium. A parcel of air given an initial upward "push" in a stable air mass will tend to return to its original position. On the other hand, when the atmosphere is in unstable equilibrium, a parcel of air given an initial upward thrust will tend to continue to rise. In the case of the marbles, the effects of gravity determined the stability of the system. What determines the stability of Earth's atmosphere?

To determine stability in the atmosphere we have to compare the temperature of a parcel of air to the temperature of the surrounding atmosphere. As we move higher and higher in the atmosphere the temperature usually decreases. The rate at which the temperature cools is called the *environmental lapse rate*. The rate at which a parcel of air cools as it rises depends on the relative humidity of the air contained in the parcel. If a parcel has a relative humidity less than 100% we say it is *dry*. A dry parcel cools at a constant rate known as the *dry adiabatic lapse rate* and is equal to about 10° Celsius per 1000 meters risen. As the parcel continues its ascent, it continues to cool, and it has less and less capacity to hold moisture. Eventually the parcel's relative humidity reaches 100% and we say it is *saturated*. The temperature of the parcel when it becomes saturated is called the *dew point temperature*.

When a parcel cools to its dew point, cloud droplets begin forming as the excess water vapor condenses on the largest aerosol particles. As the parcel keeps rising, more water condenses and the cloud droplets grow in size. If the droplets get large enough, they fall out of the cloud as precipitation. The process of condensation releases heat into the parcel and the parcel cools at a new rate called the *moist adiabatic lapse rate*. Unlike the dry adiabatic lapse rate, the moist adiabatic lapse rate varies greatly depending on the temperature of the parcel. The warmer the air, the slower the parcel cools as it rises as heat released during condensation offsets the cooling. This means that the moist adiabatic lapse rate is much less than the dry adiabatic lapse rate when the air is warm, but the two rates are nearly the same when the air is very cold.

Stability in the atmosphere is defined by comparing the environmental lapse rate to the dry adiabatic lapse rate and moist adiabatic lapse rate. An *absolutely stable* atmosphere occurs when the environmental lapse rate is less than the moist adiabatic lapse rate. Even a saturated parcel will be cooler than its surroundings at all levels and return to its original starting position. An *absolutely unstable* atmosphere occurs when the environmental lapse rate is greater than the dry adiabatic lapse rate. Even an unsaturated parcel continues to rise in this environment. In most cases, absolute instability is confined to a shallow layer of surface air on hot sunny days and only lasts for a short time. When the environmental lapse rate is somewhere between the moist adiabatic lapse rate and the dry adiabatic lapse rate, then the atmosphere is *conditionally unstable*. This means that the atmosphere's stability is dependent on the moisture content of the air. If the air is dry, then the atmosphere is stable, but if the air is saturated, the atmosphere is unstable. The atmosphere is most often in a state of conditional instability.

Atmospheric stability plays a major role in determining if cloud formation will occur on a given day. In general, an unstable or conditionally unstable atmosphere is more conducive to the development of clouds and precipitation. Sometimes a parcel can be forced to rise in a stable environment, but the atmosphere strongly resists upward motion and any clouds that form are usually fairly thin and flat. An unstable atmosphere is necessary for the development of large convective clouds like those we see during thunderstorms.

An Initial Lift

Instability in the atmosphere makes the atmosphere conducive to cloud formation, but there still needs to be some mechanism that gives the initial upward thrust to start the process. The most common lifting methods are: convection, convergence, lifting along fronts, and lifting caused by topography. Each lifting mechanism can result in clouds that have different physical characteristics.

Convection

A *parcel* may be heated by the Sun-warmed surface of Earth, become warmer than the surrounding atmosphere, and start to rise—a process called *convection*. The rising air parcel becomes diluted as it mixes with the surrounding air, losing some of its buoyancy. However, each successive air parcel following the same path rises a little higher than the previous one. If a parcel rises high enough to cool to its dew point, the moisture within it condenses and becomes visible as a cloud. On a hot summer day, the atmosphere will often start out clear, but the atmosphere is conditionally unstable, and cumulus clouds rapidly build as the day progresses and the sun heats the surface. If conditions are sufficiently unstable, these cumulus clouds can grow into towering cumulonimbus clouds that produce thunderstorms and tornadoes.

Convergence

Another process that lifts air from lower to higher altitudes is *convergence*, which is the "coming together" of surface winds. When air converges on a location, it can't pile up there forever. The converging air must go somewhere, and from Earth's surface, it can only go up. Large-scale convergence can lift a layer of air that is hundreds of kilometers across.

As it does with convection, the air cools as it rises. If it cools to its dew point temperature, water vapor in the air condenses into cloud droplets. Uplifting of air that results from convergence is usually much weaker than uplifting from convection. As a result, clouds generated through convergence don't usually build up into the towering skyscrapers that convective clouds can become.

Lifting Along Fronts

Lifting also occurs when air masses with different temperatures and moisture content encounter one another. The type of clouds that form depends on whether a cold air mass runs into a warm air mass or whether a warm air mass runs into a cold one. Cold air is generally denser than warm air, and so it typically settles close to

Figure 4. When air encounters a mountain it can't go through the mountain, so it rises. As it does, clouds and precipitation may fall on the windward side of the mountain, while it tends to be dry on the leeward side. (Image credit: Alex McClung.)

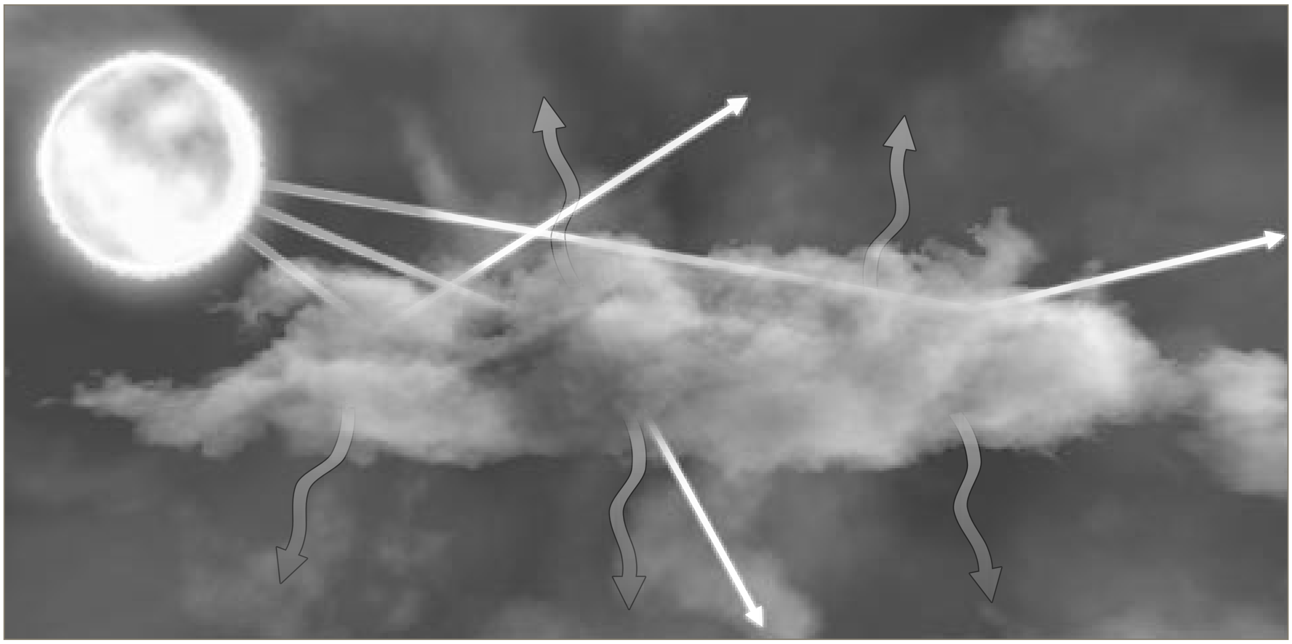
the surface. When a cold, heavy air mass moves toward a warm one, it takes the "low road" near the surface and forces the warm air up and out of its way. The convergence of a cold air mass into the space occupied by a warm one can drive warm, moist air high into the atmosphere, forming tall cumulus clouds.

In contrast, when the leading edge—the *front*—of a warm air mass nudges against a colder, denser air mass, the cold air mass acts like a boulder in a river. When the warm front reaches the cold air mass, the warm, lighter air cannot budge the cold air out of the way. Instead, it climbs up and over the edge of the cold air mass. Because warm air is less dense, the lifting of air along a warm front is gentler when compared with the lifting along a cold front. Consequently, clouds formed from the convergence of a warm air mass into a cold one are more widespread and not as tall, for example they will be thin, wispy cirrus clouds or the cotton-blanket-like stratus clouds.

Lifting Caused By Topography

When moving air encounters a mountain or a mountain range, the air is forced up the mountain's slopes. Atmospheric scientists call the process *orographic lifting*. (Orographic means "having to do with or influenced by a region's mountains or elevated terrain.") As air ascends the mountain, it cools. If the air cools enough

Figure 5a. A low-altitude cloud reflects a significant portion of the Sun's incoming radiation but has little impact on Earth's outgoing thermal radiation. Overall, low clouds tend to contribute to cooling the planet. (Image credit: Alex McClung.)



to reach its dew point, the water vapor in the air condenses and forms a cloud. As illustrated in **Figure 4**, clouds and precipitation often occur on the side of the mountain facing the wind—the *windward side*—and it will be very dry on the other side of the mountain—the *leeward side*.

How Clouds Impact Earth's Climate

Depending on their characteristics and height in the atmosphere, clouds can influence the energy balance in different ways. Clouds can block a significant portion of the Sun's incoming radiation from reaching the Earth's surface, as anyone who has had a day at the beach interrupted by heavy clouds can tell you. Due to the shadowing effect of clouds, the Earth's surface tends to be cooler than it would otherwise be. Perhaps not as obvious to the casual observer, clouds also act like a radiative "blanket" by absorbing the thermal infrared radiation (a.k.a., heat) that the Earth's surface emits back toward space. As a result, the surface under the cloud doesn't cool as rapidly as it would if no clouds were present.

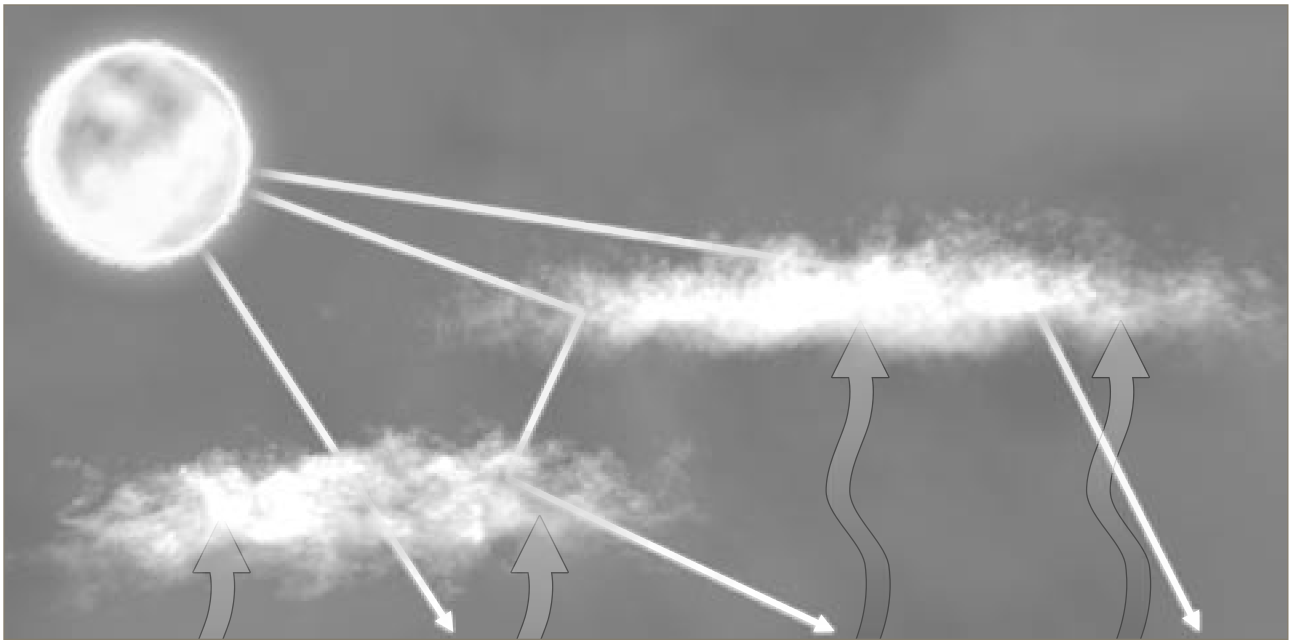
The cloud's height in the atmosphere influences how effective it is at trapping outgoing heat. A cloud that is higher in the atmosphere will emit less heat to space than an identical cloud at a lower altitude. Meanwhile, the clouds optical thickness (*thickness* in this case means how much light the cloud can intercept, rather than a specific physical thickness) is more important than its altitude in determining how much incoming solar energy the cloud reflects back to space.

Because of clouds' competing radiative effects (reflecting solar radiation cools the planet, while trapping outgoing heat warms the planet), predicting the impact of any particular cloud on the temperature of Earth's climate system is difficult. In a global sense, the net effect of clouds depends on how much of the Earth's surface they cover, their thickness and altitude, the size of the condensed particles, and the amount of water and ice they contain.

In general, low-altitude clouds (like stratus clouds) tend to be relatively thick optically, and they reflect a significant portion of the incoming solar radiation [see **Figure 5a**]. They have little impact on emitted infrared radiation, however, because these low, warm clouds have almost the same temperature as Earth's surface. With their relatively warm temperatures, these low-altitude clouds are typically composed of spherical water droplets, and their overall impact is to cool the planet. Conversely, high-altitude clouds (like cirrus) are usually quite thin optically. They therefore reflect little solar radiation but still absorb some of the outgoing thermal radiation [see **Figure 5b**]. These high-altitude clouds are composed mostly of ice crystals, with a wide variety of shapes and sizes, and their overall impact is to warm the planet.

Research on clouds and the climate indicates that overall, clouds' cooling effects are more powerful than their warming effects. But how the balance between clouds' cooling and warming influences might change in the future is still very uncertain.

Figure 5b. A high-altitude cloud has little impact on the Sun's incoming radiation but does absorb a significant amount of Earth's outgoing radiation. Overall, high clouds tend to contribute to warming the planet. (Image credit: Alex McClung.)



The Difficulties of Predicting How Clouds Impact Earth's Climate

A critical question for Earth scientists is this: Will an enhanced greenhouse effect produce changes in clouds that further influence global surface temperatures? The question is a tough one. The main uncertainties in global-change predictions come from inadequate representation of clouds in climate models: the models do net yet have sophisticated enough descriptions of cloud processes, and scientists do not have enough cloud observations to verify the model predictions.

Another modeling problem is that clouds change almost instantaneously compared to the rest of the climate system. For example, cumulus clouds can arise in a matter of minutes, even seconds, and the entire life cycle of a massive thunderstorm plays out within a few hours. Not only that, but a thunderstorm might only impact tens of miles of the Earth's surface during its life cycle. These small space and time scales make clouds extremely difficult to simulate in models.

Clouds absorb and reflect solar radiation and absorb and emit thermal radiation. The resulting heating affects the atmospheric circulation and water content, which in turn determines where clouds form. This coupling of the atmospheric circulation, clouds, and radiative heating constitutes a *feedback process*—meaning that changes in any one of these things will impact and "feed off" the others. Many scientists consider the uncertainty about the feedback of clouds on the climate to be the major obstacle to credible predictions of climate change.

Observing Clouds from Space

People have been observing and keeping records of clouds for generations. These ground-based records have made important contributions to our current understanding of clouds, but they don't provide scientists with the required detailed global cloud database to help them continue to improve model representations of clouds. Specifically, scientists require frequent observations (at least daily), over global scales (including remote ocean and land regions), and at wavelengths throughout the electromagnetic spectrum (visible, infrared, and microwave portions of the spectrum). Ground-based measurements make significant contributions, particularly to temporal coverage, but are limited to mostly land areas. Satellite observations complement and extend the ground-based observations by providing increased spatial coverage and multiple observational capabilities. The Earth-Sun System Division in NASA's Science Mission Directorate helps to provide these satellite observations. Several missions already provide unprecedented Earth observing capabilities that allow for global observations of the planet at a reasonable cost, and more are planned for the future with even more comprehensive observing capabilities. For example, the Afternoon Constellation or "A-Train" is a grouping of satellites flying in very close proximity to one another that will provide unprecedented ability to study clouds from space (for more information please see *NASA Facts FS-2003-1-053-GSFC*).

Using all of this information, researchers will have at their disposal the most comprehensive information on clouds they have ever obtained. This information should help them better determine the role that clouds play in global climate. These new missions build on the capabilities of current missions that study clouds. They not only observe where and when clouds occur, but also collect measurements on their vertical structure—such as altitude, optical depth, thickness, and layering—and their microphysical properties—such as droplet size, and how much ice and/or water they contain.

Summary

Satellite observations of global cloudiness, like the image shown in **Figure 1**, are leading to the most accurate and comprehensive database of Earth's clouds ever obtained. The observations will improve as future satellite missions with greater observing capabilities are launched. These observations are important for improving and validating models of Earth's climate, and for seasonal and longer-term climate predictions. Scientists are gaining new insights into how clouds control atmospheric and surface temperature, atmospheric humidity, and atmospheric and oceanic circulation and precipitation patterns, all of which affect our daily lives in fundamental ways. The Earth-Sun System Division in NASA's Science Mission Directorate is dedicated to connecting these Earth observations to practical applications in society so that its *science results serve society* and the maximum number of people possible benefit from NASA research. This is a manifestation of NASA's vision to *improve life here* and its mission to *understand and protect our home planet*.

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Goddard Institute for Space Studies Introduction to Clouds
http://icp.giss.nasa.gov/education/cloudintro/

Students' Cloud Observations On-Line (S'COOL)
http://asd-www.larc.nasa.gov/SCOOL/