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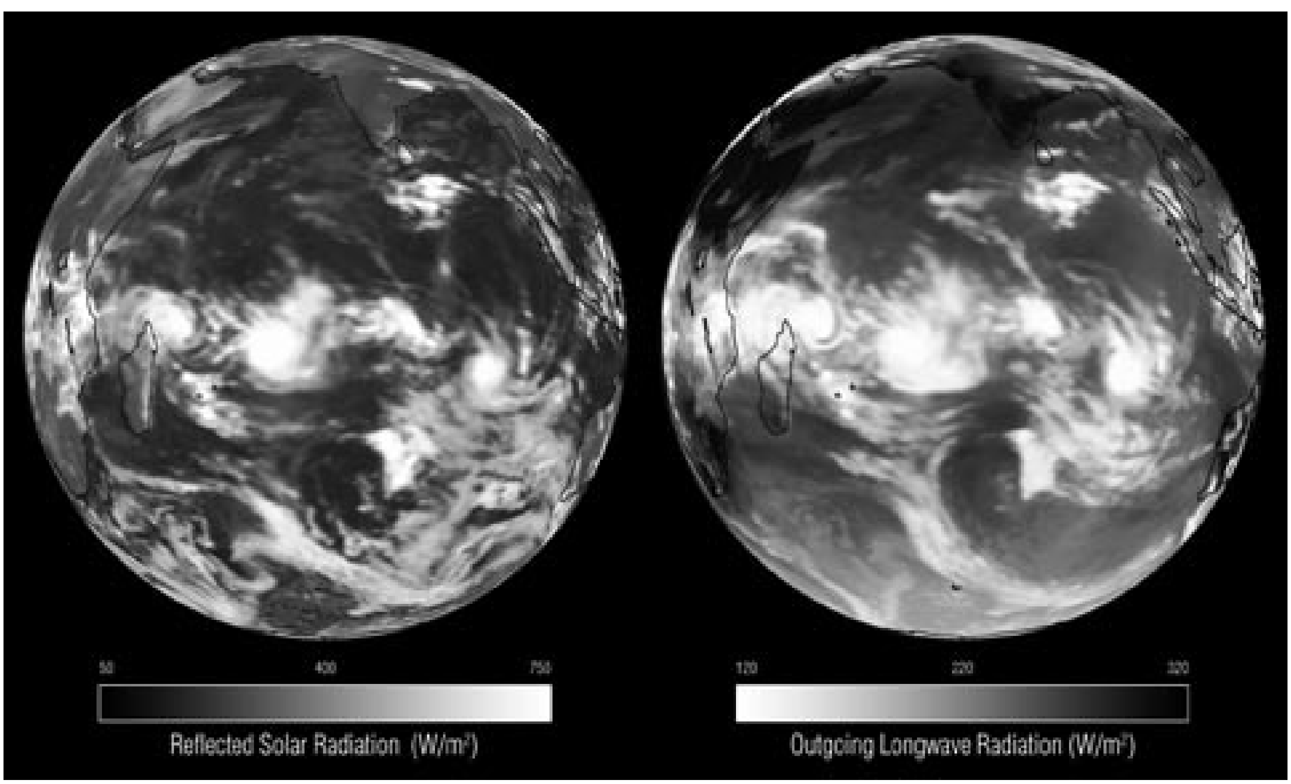
The Balance of Power in the Earth-Sun System

The Sun is the major source of energy for Earth's oceans, atmosphere, land, and biosphere. Averaged over an entire year, approximately 342 watts of solar energy fall upon every square meter of Earth. This is a tremendous amount of energy—44 quadrillion (4.4 x 10^{16}) watts of power to be exact. As a comparison, a large electric power plant produces about 1 billion (1 x 10^{9}) watts of power. It would take 44 million such power plants to equal the energy coming from the Sun.

With all that energy out there, it seems as if Earth should just keep getting hotter. Why doesn't this happen?

At the same time the Sun's energy heats the planet, the planet radiates energy that we can't see with our eyes (*longwave radiation* or *heat*) back to space. As an object heats up, it starts to dramatically increase the amount of heat energy it gives off. So the more Earth heats up, the more rapidly it will lose energy to space.

Figure 1: The Clouds and the Earth's Radiant Energy System (CERES) sensors on NASA's Terra and Aqua satellites monitor energy balance from space and can detect the amount of incoming solar radiation and outgoing longwave radiation (heat). Terra-CERES obtained these images of the Indian Ocean on February 11, 2003, showing four active tropical cyclones (the bright white areas in the center of each image). The cyclones are areas of thick cloud cover that tend to reflect a large amount of incoming solar energy back to space (see the left image), but at the same time, reduce the amount of outgoing heat lost to space (see the right image). Contrast the areas that do not have cloud cover (darker colored regions) to get a sense for how much impact the clouds have on incoming and outgoing energy. (Image credit: NASA CERES team.)



Energy Balance

If we measure the total amount of energy Earth receives from the Sun and then subtract the total amount of energy Earth reflects and emits back to space, we arrive at a number called an *energy budget*. Over time, Earth's climate system tends toward an *energy balance* between incoming solar energy and outgoing thermal energy (heat) [see **Figure 1**]. If more solar energy comes in, then Earth warms and will emit more heat to space to restore the balance.*

How the Sun's Energy is Distributed Over the Earth

Not all of the Sun's energy that enters Earth's atmosphere makes it to the surface. The atmosphere reflects some of the incoming solar energy back to space immediately and absorbs still more energy before it can reach the surface. The remaining energy strikes Earth and warms the surface. How does Earth's climate system distribute the energy that it receives? To understand the answer to this question, we need to first consider the position of Earth relative to the Sun.

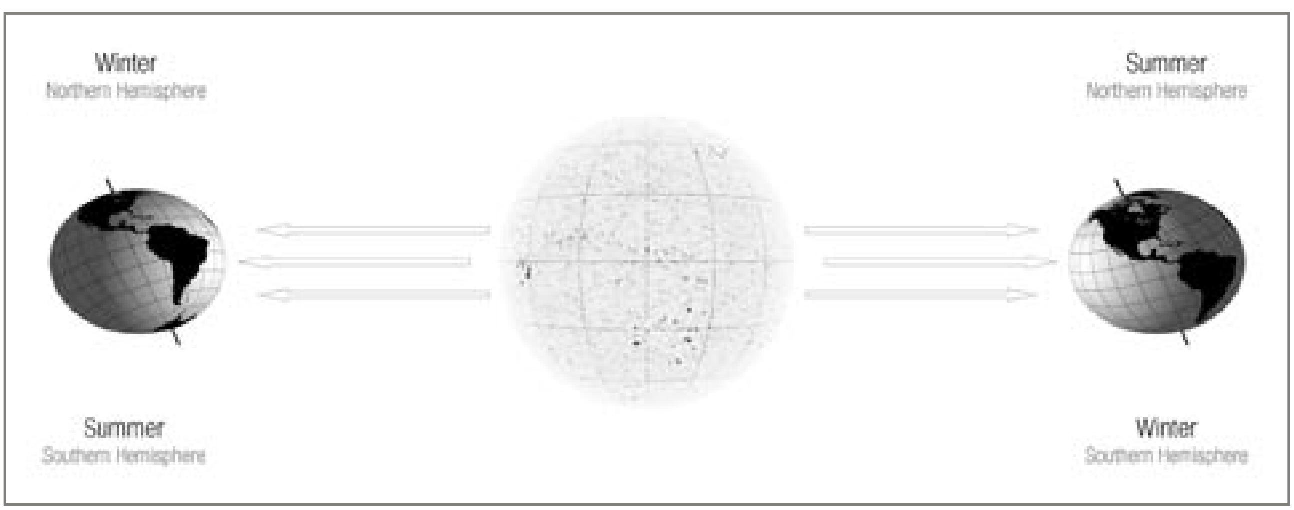
Earth maintains an eliptical orbit around the Sun, and is tilted relative to the Sun's plane of orbit. (A plane refers to an imaginary flat surface.) It might be helpful to imagine the Earth rotating around the rim of a dinner plate with the Sun cutting through the middle of the plate. At the same time, Earth itself spins on its axis each day. When the Earth sits in its plane, we find that the North Pole does not stick straight up and down—that is to say, it's not perpendicular (at a 90° angle) to the plane but rather tilts at a 23.5° angle relative to the vertical plane, pointing toward the North Star, Polaris. It is this tilt of the Earth's axis that causes the position of the Earth's Poles to change relative to the Sun over the course of a year and explains why we have seasons [see **Figure 2**].

*Recent research suggests that the amount of incoming solar energy Earth receives from the Sun is greater than the amount Earth returns to space as heat—evidence that Earth is warming.

The amount of change from season to season varies depending on where you are on the planet's surface. Near the Equator, the amount of solar energy received stays fairly constant throughout the year and there is not much difference between summer and winter. In contrast, areas near the Poles experience significant differences between summer and winter. In the hemisphere where it is summer, the Pole points toward the Sun and receives almost as much solar energy as the Equator. Meanwhile, in the winter hemisphere, the Pole points away from the Sun, and high latitudes receive little if any solar energy.

Given enough time and barring outside influences, Earth's climate system will naturally distribute heat evenly over Earth's surface. Winds and ocean currents help to achieve this balance. In the winter hemisphere, there is much more heat energy concentrated in the tropics than there is at the Pole. This imbalance in heating aids the formation of the intense mid-latitude storms we frequently see during winter. As these storms move across the planet they transport heat energy from surplus areas in the tropics to deficit areas in polar regions and effectively even out the distribution of energy over the planet. By contrast, in the summer hemisphere, the difference in heating between the Pole

Figure 2: The Earth is always tilted 23.5° away from perpindicular in the Sun's orbit plane. Because of this tilt, as Earth revolves around the Sun over the course of a year, the position of the North and South Poles changes relative to the Sun. Earth's Northern Hemishpere receives more sunlight during the months of June, July and August and grows warmer, while Earth's Southern Hemisphere receives less sunlight and grows colder. In December, January, and February, the position changes so that the Southern Hemisphere receives more sunlight than the Northern Hemisphere, and the seasons reverse. The Equator on the other hand stays in nearly the same position relative to the Sun throughout the year, so the tropics experience much less seasonal variation. (Image credit: Alex McClung.)



and the tropics is not nearly so large. As a result, we don't see as many intense mid-latitude storms during the summer months. The storms that do form during the summer tend to be weaker and more localized.

Factors that Influence the Earth-Sun Energy Budget

If Earth was a ball of rock with no atmosphere, and if we assume that the surface of the rock reflects 30% of all the solar energy that hits it, a simple calculation equating incoming solar energy and outgoing thermal energy suggests that the global average temperature should be 0° F (-18°C). But we all know Earth is nowhere near that cold. Why is that? What else is going on?

To explain Earth's actual energy balance, we must include the influence of various *forcings*—Earth-system characteristics that cause the energy budget to shift away from its balanced state. In fact, it turns out that just a small percentage change in any one forcing could have a significant impact on Earth's energy balance. Furthermore, changes in any one forcing could impact the other forcings. Sometimes a change in one Earth system characteristic causes another characteristic of the system to change, which in turn enhances the change in the original characteristic—scientist's call these *feedback loops* as one change "feeds" off the other [see **Figure 3**].

Greenhouse Gases

The primary reason Earth is not the frigid, inhospitable ball of rock described above is its atmosphere. When Earth's surface absorbs solar radiation, it warms and emits thermal radiation back toward space. However, only some of the heat radiated directly from the surface actually makes it back into space; atmospheric gases, such as water vapor and carbon dioxide, absorb the rest. The gases, in turn, re-radiate some of the heat they absorb. Because these atmospheric gases radiate energy in all directions, some of the energy escapes to space and some remains in the Earth system, where it continues to warm the atmosphere and Earth's surface. This trapping of heat by gases like carbon dioxide and water vapor is referred to as the *greenhouse effect*, and the gases that produce this effect are called *greenhouse gases*.

An increase in the amount of greenhouse gases present in Earth's atmosphere (in particular, the release of carbon dioxide from burning oil, gas, and coal from human activities) could have serious impacts on energy balance—which could lead to changes in the average temperature of the planet. Scientists predict that as temperatures in the atmosphere increase, the amount of water vapor will also increase, thereby acting as a *positive feedback loop*—meaning that this series of changes would serve to further increase warming.

Clouds

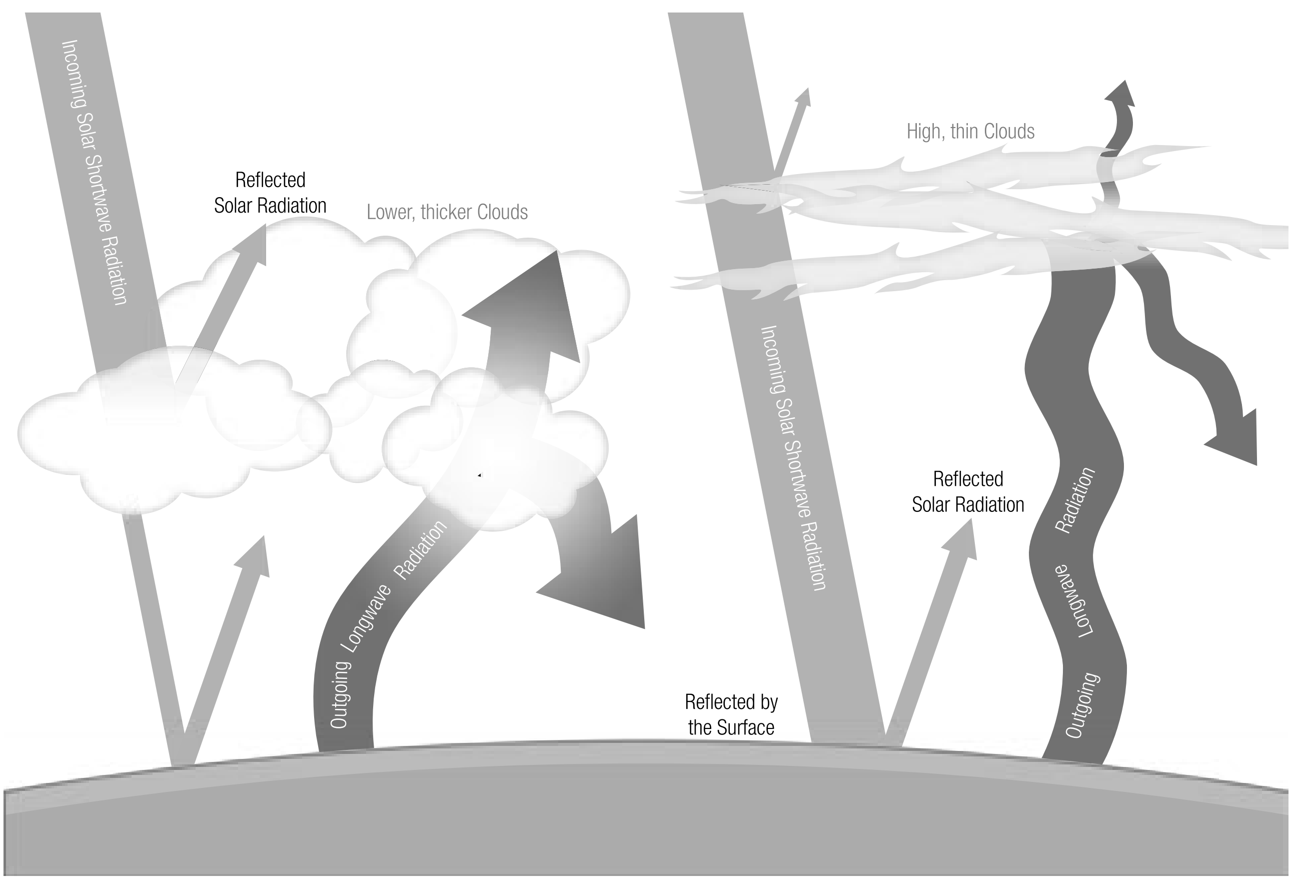
Another prominent feature of our atmosphere that impacts energy balance is the presence of clouds [see **Figure 4a**]. Depending on their characteristics and height in the atmosphere, clouds can influence the energy balance in different ways. Clouds can block a significant portion of the Sun's incoming radiation from reaching 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, Earth's surface tends to be cooler than it would otherwise be, like the shading that a beach umbrella provides on a hot sunny day. Perhaps not as obvious to the casual observer, clouds also act like a radiative "blanket" by absorbing the thermal infrared radiation (heat) that 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 [see **Figure 4a** *and* **4b**]. 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 energy warms the planet), predicting the impact of any particular cloud on the temperature on Earth's climate system is difficult. In a global sense, the net effect of clouds depends on how much of Earth's surface they cover, their thickness and altitude, the size of the condensed particles, and the amount of water and ice they

Figure 3: This picture was taken from a research vessel as it moved through the Ross Sea in Antarctica in 1997. The presence of ice changes the reflective properties of the ocean surface. If the amount of sea ice decreases as climate warms, then that means less incoming solar radiation is reflected away to space and more is absorbed by the ocean, leading to temperature increases, which in turn could lead to more sea ice melting. This creates a positive feedback loop, since the sequence of events enhances warming. (Image Credit: Michael Van Woert, NOAA NESDIS, ORA.)

Figure 4a (top) and Figure 4b (bottom): Cumulus clouds, like the one in front of the Sun in **Figure 4a**, are effective at reflecting solar energy while having a neglible effect on outgoing longwave radiation (heat) from the planet (as shown on the left side of the **Figure 4b**). The clouds have a net cooling effect on the planet. The higher, thin cirrus clouds in **Figure 4a** allow most of the solar energy to pass through, but they trap a large portion of the heat energy of the planet (as shown on the right side of **Figure 4b**). They have a net warming effect on the planet. (**Figure 4a** credit: Reto Stöckli. **Figure 4b** credit: Alex McClung.)



contain. For a complete treatment of the subject of clouds please see our Clouds Fact Sheet (NASA Facts 2005-9-073-GSFC).

Atmospheric Aerosols

The presence of aerosols in the atmosphere can also have a significant impact on Earth's energy budget. Aerosols are tiny particles (liquids or solids) in our atmosphere. Some occur naturally, originating from volcanoes, dust storms, forest and grassland fires, living vegetation, and sea spray. Human activities, such as the burning of fossil fuels and the alteration of natural surface cover, also generate aerosols. Averaged over the globe, aerosols made by human activities currently account for about half of the total mass of aerosols in our atmosphere.

Scientists are still struggling to understand the net impact aerosols have on Earth's energy budget. The answer seems to depend critically on the physical and chemical makeup of the aerosols, the concentration of aerosols present, how effective the aerosols are at absorbing incoming solar radiation, how large the aerosols are, and how high the aerosols are in the atmosphere.

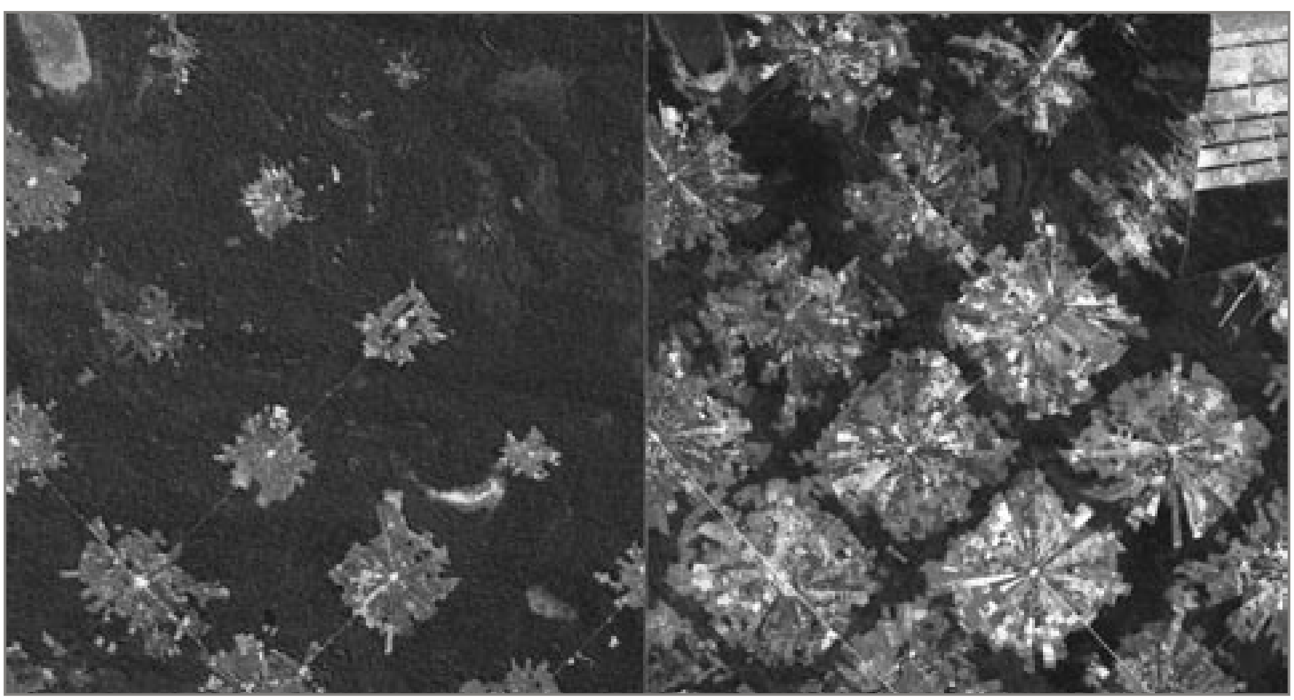
Even more confusing, the presence of aerosols can impact the characteristics of clouds, which themselves impact Earth's energy budget. A change in the amount of aerosols in the atmosphere over a particular region impacts the characteristics of clouds that form in that region. As the concentration of aerosols increases, the water in the cloud gets spread over many more particles, each of which is correspondingly smaller. An increased number of smaller particles in a cloud means that it will take longer for individual cloud droplets to grow large enough to fall as rain. Scientists found in some cases, aerosols completely choke off the formation of clouds. In this way, the presence of aerosols can change the frequency of cloud occurrence, cloud thickness, and rainfall amounts. For a complete treatment of the subject of aerosols please see our Aerosols Fact Sheet (*NASA Facts 2005-9-072-GSFC*).

Surface Absorption and Reflection

When we first described the relationship between the amount of solar energy Earth reflects and its average global temperature, we assumed that the surface was the same everywhere and reflected 30% of the energy that it received. The truth is that Earth's surface is highly variable and the amount reflected (referred to as *albedo*) constantly changes. Scientists have to consider the albedo of the surface when they attempt to make energy budget calculations.

In addition, the presence of snow and ice changes the reflective properties of Earth's surface [see **Figure 3**]. Changing the amount of snow and ice on Earth will

Figure 5: Shown here are two images of the same area in Bolivia, one acquired by Landsat 5 in 1986 and the other by the Advanced Spaceborne Thermal Emission and Reflection Radiometer on the Terra spacecraft in 2001. Notice how much the land surface has been altered in 15 years and how much brighter the surface is in the image on the right. Clearly, largescale changes in land cover like the one shown here can alter the energy budget. (Image credit: NASA Landsat and Terra teams.)



change the global energy balance and therefore the global temperature—a feedback process. If the surface of the Earth becomes cold enough, snow and ice will cover more of the surface and increase the amount of sunlight reflected back to space, causing the planet to cool even more. Conversely, as the planet warms, the amount of snow and ice on the surface will decrease, and so the Earth will reflect less energy back to space, causing even more warming.

Changes in land cover can also impact the reflective properties of Earth's surface [see **Figure 5**]. When vegetation is cleared from land surfaces (such as in deforestation or agricultural burning), the bare surface becomes brighter and reflects more sunlight back to space than the vegetated surface, which might seem to suggest that cooling would occur. However, judging the overall impact of land cover change on the Earth's energy budget is not as straightforward as was the case for snow- and ice-covered surfaces. Although the bare surface is more reflective, the loss of evaporative cooling and shade that plants provide would have a warming effect. In addition, burning biomass releases carbon dioxide (CO_2), adding greenhouse gases to the atmosphere. By removing the vegetation, we also reduce the land surface's potential to absorb carbon dioxide during photosynthesis. Making energy budget calculations even more complicated, the smoke from the burning vegetation also contains tiny aerosols, another source of uncertainty in Earth's radiation budget.

Space-Based Observations Lead to Improved Understanding of Energy Budget

To reduce the uncertainties associated with calculating energy budget, researchers must develop models that can simulate Earth's climate. These models are a set of mathematical equations that reproduce the variability shown in Earth's climate at both regional and global scales. In order to be useful for energy budget studies, the models have to accurately reproduce physical phenomena such as El Niño, Earth's day-night and seasonal cycles, and the interannual variability in Earth's climate system. The models must also reproduce the changes in energy balance that are caused by changing aerosols, water vapor, clouds, and surface properties. Only then can we begin to trust the models to produce accurate predictions of how energy balance changes will impact the Earth's climate.

Clearly, this is no easy task and it requires the full effort of NASA and a wide variety of other domestic and international partners. Scientists make use of measurements from a wide variety of ground-based sources including laboratory studies of cloud particles and aerosol properties, and aircraft and surface-based field experiment measurements. However, ground-based measurements alone can't offer the detailed observations scientists need to fully understand a complex subject like Earth's energy budget. Satellite observations offer the potential of providing the continuous global observations that scientists require.

The Earth-Sun System Division in NASA's Science Mission Directorate is helping to provide these satellite observations. Several Earth observing missions already make 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 and aerosols from space (for more information, please see NASA Facts *FS-2003-1-053-GSFC*).

Summary

Energy budget studies represent an important research focus area for the Earth-Sun System Division in NASA's Science Mission Directorate. Satellite observations are playing an important role in improving our understanding of this complex subject. NASA seeks to connect Earth observations and model results 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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