NASA Facts

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771
(301) 286-8955

February 1999

The Earth Observing System Terra Series

These articles focus on the overarching science priorities of the EOS Terra mission

Earth's Energy Balance

"Why Isn't Earth Hot as an Oven?"

Sunlight is the source of energy for the Earth’s oceans, atmosphere, land, and biosphere. This energy serves to heat the Earth to temperatures far above the minus 454 degrees Fahrenheit (3 degrees Kelvin) of deep space. Averaged over an entire year and the entire Earth, the sun deposits 342 Watts of energy into every square meter of the Earth. This is a very large amount of heat—4.4 x 10^{16} watts of power that the sun sends to the Earth/atmosphere system. For comparison, a large electric power plant would produce 100 million watts of power, or 10^8 watts. It would take 440 million such power plants to equal the energy coming to the Earth from the sun—roughly one for every ten people on the Earth! Where does all the Sun's heat go? Why doesn’t the Earth just keep getting hotter?

Most of the sun’s heat is deposited into the tropics of the Earth. This is because the Earth’s rotational axis is almost perpendicular to the plane of Earth’s orbit around the sun. The polar latitudes receive on average much less solar heating than the equator. If the tilt of the Earth’s axis were exactly perpendicular to the orbit plane around the sun, then there would be no seasons! Climate in January would be the same as climate in April or July, all over the Earth. But the Earth’s rotational axis tilts 23.5 degrees away from perpendicular. Consequently, during one part of the orbit around the sun, the North Pole will be tilted 23.5 degrees toward the sun and will

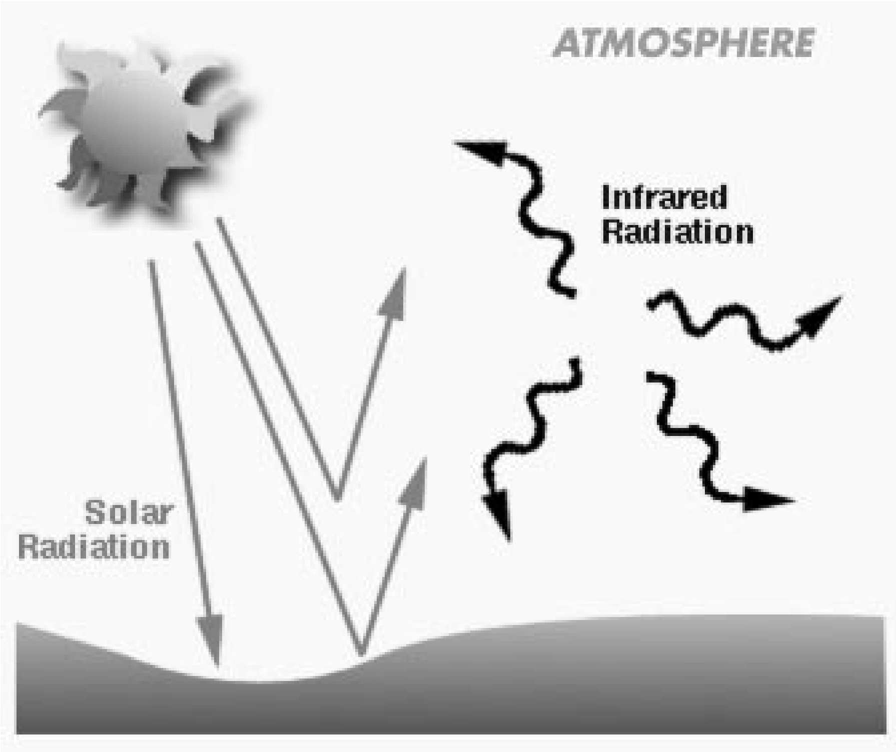

Figure 1. The atmospheric greenhouse effect. Shortwave solar radiation passes through the clear atmosphere relatively unimpeded, but longwave infreared radiation emitted by the warm surface of the Earth is absorbed partially and then re-emitted by a number of trace gases such as water vapor and carbon dioxide.

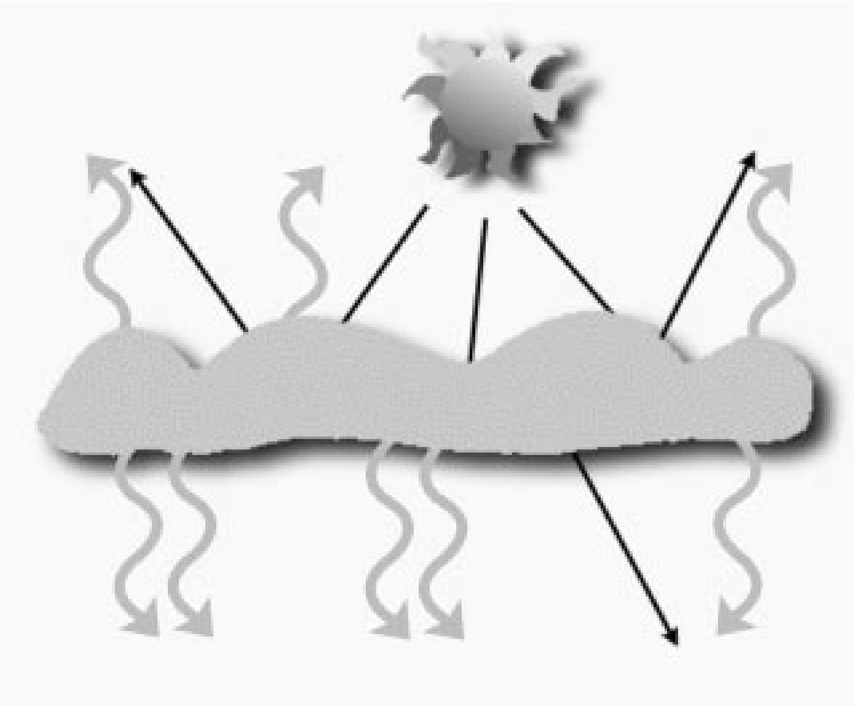

Figure 2. Stratus clouds, which are mostly composed of liquid water droplets, reflect most of the incoming shortwave radiation (thin lines), but re-emit large amounts of outgoing longwave radiation (thick lines). Their overall effect is to warm the planet.

be in sunlight 24 hours a day. Six months later at the opposite side of the orbit around the sun, the North Pole will be in total darkness 24 hours a day. Why is this important? The amount of solar heating of the polar latitudes varies greatly through the year. In the summer, polar latitudes receive almost as much solar energy as the tropics, while in the winter they receive no solar heat at all. Meanwhile, the tropics receive by comparison roughly constant solar heating throughout the year (hence the small seasonal cycles there). As a result, in the winter hemisphere, the difference in solar heating between the equator and the pole is very large—a situation perfect for driving a strong "heat engine," or circulation of the atmosphere. This energy difference drives large mid-latitude storm systems as heat moves from the surplus in the equator to the deficit in the polar regions. In contrast, the summer has very similar heating at the equator and poles, such that the heat engine slows down, and mid-latitude storms lose their source of energy. Summer storms tend to be very small scale and local.

Solar heating of the Earth and its atmosphere drives the large-scale atmospheric circulation patterns, and even the seasons. The difference in solar heating between day and night also drives the strong diurnal (or daily) cycle of surface temperature over land. But with all this solar heating going on, we still haven't answered our earlier question: Why doesn't the Earth just keep getting hotter?

The answer might be loosely called the yang and yin, or the "duality of radiation fluxes." At the same time the solar energy that we can see with our eyes is heating the planet, there is radiation being emitted at much longer wavelengths that our eyes do not see—called "thermal infrared radiation" (basically heat). The amount of heat emitted from a solid surface is proportional to the fourth power of the temperature of the surface. So as the temperature of the Earth rises, it rapidly emits and loses to space an increasing amount of heat. If the Earth were a ball of rock with no atmosphere, a simple calculation that equates the solar energy absorbed by the Earth to the heat emitted by the Earth would predict the global average Earth temperature to be 0 degrees Fahrenheit, or 255 Kelvin—very cold, and not the Earth as we know it (this scenario assumes that an average rock reflects 30 percent of all light that hits it).

Earth's Invisible Blanket

Atmospheric gases, such as water vapor and carbon dioxide, absorb the heat emitted from the surface, capturing it in the atmosphere (Figure 1). Because atmospheric temperature decreases with altitude, the heat emission of the atmosphere is at a much lower temperature than the surface. So the Earth and atmosphere keep heating up until the heat emitted roughly balances with the amount of sunlight absorbed. This trapping of heat by carbon dioxide and water vapor is typically called the "greenhouse effect," and these gases are referred to as "greenhouse gases." It is the increase in these gases with time (led by carbon dioxide release from burning oil, gas, and coal) that leads to the potential for future climate change. In fact, most theoretical models predict that as temperatures in the atmosphere increase, the amount of water vapor will increase, thereby acting as a "positive feedback" loop to further increase atmospheric temperatures.

Clouds: A hot topic or are we made in the shade?

But carbon dioxide and water vapor are not the whole story. As we all know from days at the beach, clouds block much of the solar energy and reflect it back to space before it can be absorbed by the Earth, the atmosphere, or the sunbather! The more plentiful and thicker the clouds are, the cooler the Earth. At the same time, clouds also act like greenhouse gases—they block the emission of heat to space and inhibit the ability of the planet to release its absorbed solar energy (See Changing Global Cloudiness FS-1999-**-***-GSFC). To complicate matters further, the altitude of clouds changes the amount of thermal infrared blocking. Once again, this effect is the result of the decrease in temperature with altitude—high clouds are colder, and are more effective at absorbing the surface-emitted heat in the atmosphere, while they emit very little to space because of their cold temperatures! So it turns out that clouds can either act to cool or warm the planet depending on how much of the Earth they cover, how thick they are, and how high they are. The effectiveness of clouds depends on whether they are low-altitude warm clouds made of spherical water droplets (Figure 2), or whether they are high-altitude cold clouds made up of ice crystals with a wide range of crystal shapes and sizes (Figure 3). In the late 1980s, the NASA Earth Radiation Budget Experiment (ERBE) determined for the first time that on average, clouds tend to cool the planet. The cloud reflection of sunlight back to space dominates over the clouds' greenhouse effect. In fact, the planet would on average be some 20°F hotter if we removed clouds from the atmosphere. Recently, attempts have been made to combine the ERBE satellite measurements of the radiative energy balance at the top of the atmosphere with measurements of the radiation balance at the surface. The objective of this combination is to infer the amount of radiation absorbed by the intervening atmosphere. Unexpectedly, this combination implies that the atmosphere absorbs more radiation than is theoretically predicted. Are the observations wrong or is the theory? Do we understand clouds?

Given the large impact of clouds on the radiative energy balance, the critical question now becomes: What effect will clouds have on surface temperatures if global climate changes in the next century? No one knows. Clouds could act to dampen any greenhouse gas warming by increasing cloud cover, increasing thickness, or by decreasing in altitude. Conversely, clouds could act to increase warming of the planet if the opposite trends occur. In fact, the climate is so sensitive to how clouds might change, that our current best models of global climate can vary in their global warming predictions by more than a factor of three depending on how we try to model the clouds.

So why can't we model clouds? The biggest problem is that clouds are almost explosive in nature when compared to the rest of the climate system. Cumulus clouds can form in seconds to minutes, and the entire life cycle of a massive thunderstorm can be measured in hours. This thunderstorm cloud may only cover 20 to 50 miles of the Earth's surface, while our best global climate models on the world's fastest supercomputers can only track a single column of the surface and atmosphere every 50 to 200 miles.

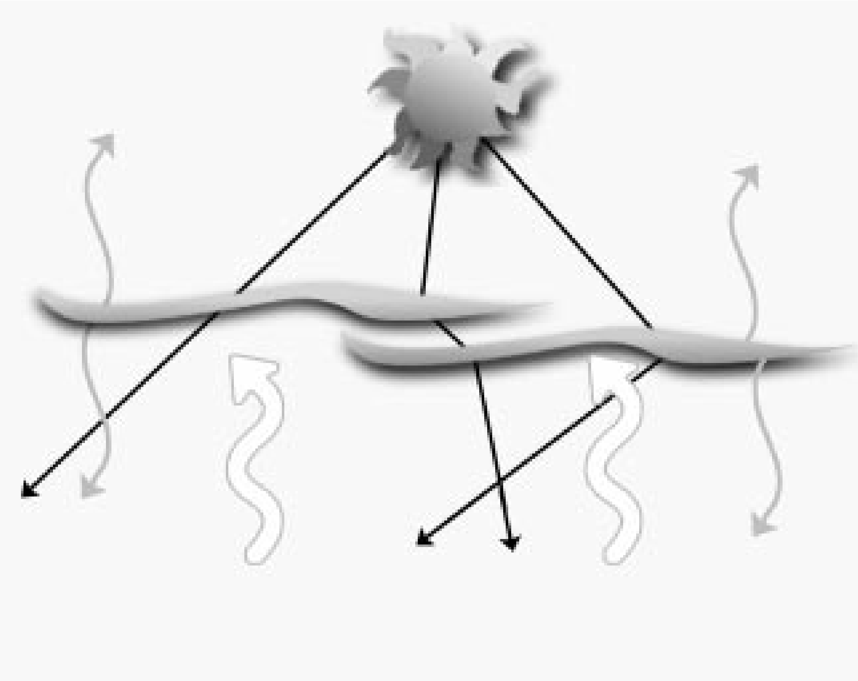

Figure 3. Cirrus clouds, which are mostly composed of ice crystals, transmit most of the incoming shortwave radiation (thin lines), but trap some of the outgoing longwave radiation (thick lines). Their overall effect is to cool the Earth.

Surface Absorption and Reflection

Clouds are just one example of things that can change Earth's radiant energy balance. Snow and ice are other examples. If the surface of the Earth becomes cold enough, snow and ice will cover the surface and increase the amount of sunlight reflected back to space. So the amount of snow and ice on the Earth will change the global energy balance and therefore the global temperature. Conversely, as the planet warms, the amount of snow and ice on the surface will decrease, and so the planet will warm further—this is called a "positive feedback" because it tends to amplify climate change.

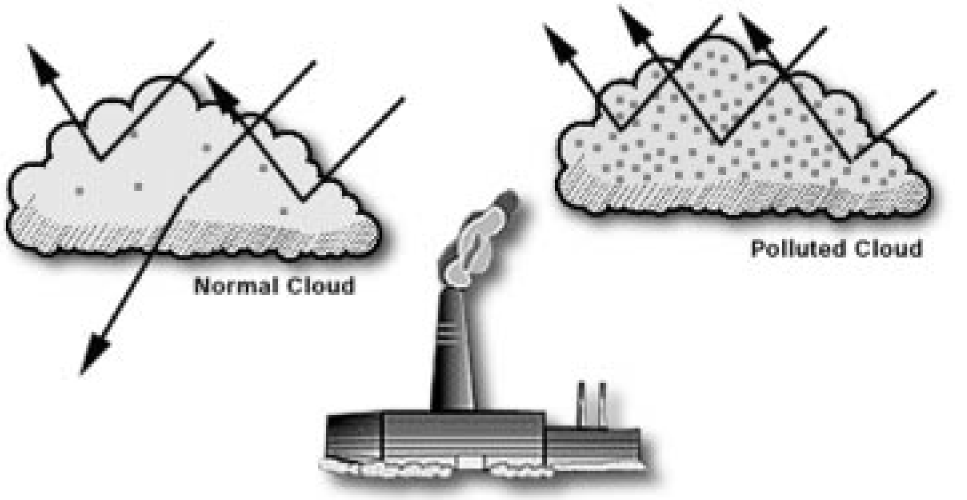

Figure 4. Clouds polluted by aerosols from factories have more numerous and smaller drops, causing the cloud to become brighter and reflect more of the Sun's radiative energy.

Less obvious, but still important, when vegetation is cleared from land surfaces (such as in deforestation or agricultural burning), the bare surface reflects more sunlight back to space and there is a net cooling effect. But, there is also a counter productive greenhouse gas effect that comes from deforestation and biomass burning—the release of carbon dioxide, as well as elimination of vegetation that would otherwise absorb carbon dioxide from the atmosphere during photosynthesis. Unfortunately, while deforestation/reforestation may take place on annual to decadal time scales, the lifetime of carbon dioxide in the atmosphere is 50 to more than 100 years. Consequently, the solar reflectance cooling and greenhouse gas warming due to biomass burning take place at very different time scales, leading to an initial cooling followed later by a warming trend.

Atmospheric Aerosols: Fossil Fuel and Biomass Burning

There is yet another impact of biomass burning on the energy budget of the planet—such burning produces tiny smoke particles called "aerosols" (see Aerosols FS-1999-**-***-GSFC). These aerosols can be either cooling or warming depending on how much solar radiation they absorb versus how much of it they scatter back to space. Close to the burning area, smoke clouds can look almost black, indicating strong absorption, while further downwind they may look white, indicating weaker or no absorption. Fossil fuel burning in automobiles, factories, and power plants also add aerosols to the atmosphere while polluting clouds (Figure 4). These aerosols are thought to absorb less solar radiation than those produced by biomass burning, but the exact amount of absorption from each type of aerosol is not yet known. Overall, we do not even know if aerosols are warming or cooling the planet! This depends critically on how much aerosol is present, how absorptive the aerosol is, how large the aerosol particles are, and how high the aerosol is in the atmosphere. For example, the aerosols emitted by the Mt. Pinatubo eruption in 1991 were very small particles that absorbed very little sunlight and primarily reflected it. As predicted, the aerosols from Mt. Pinatubo acted to cool the planet for a couple of years before settling out of the atmosphere. Man-made aerosols tend to be processed out of the atmosphere by clouds within a few weeks.

As the number of aerosols increases, the water in the cloud gets spread over many more particles, each of which is correspondingly smaller. Smaller particles fall more slowly in the atmosphere, and decrease the amount of rainfall. In this way, changing aerosols in the atmosphere can change the frequency of cloud occurrence, cloud thickness, and rainfall amounts. Even the tiny aerosols (typically less than 50 millionths of an inch or 1 micron across) can affect the clouds, which in turn can change the radiation balance of the planet. Thus, aerosols can have both a direct effect on the energy balance, as well as an indirect effect (through clouds). It is thought that the indirect effect of aerosols can be even larger than their direct effect, but at present it is not known whether such an effect is a net cooling or warming of the planet.

From Measurements to Climate Models

With clouds, aerosols, and surface properties varying greatly over the Earth, and with our inability to model Earth's complex climate system, we need a hierarchy of measurements varying from laboratory studies of cloud particles and aerosol properties, through aircraft and surface-based field experiment measurements, to observations of the entire Earth from space. Only from space, however, can we observe the surface, aerosol, and cloud changes in anything approaching a complete set of conditions occurring in the climate system.

Ultimately, we are searching for a set of mathematical models that allow us to span the incredibly large range of space and time scales important to aerosols, water vapor, clouds, the land surface, and the oceans. These models must be capable of reproducing the variability shown in the data at both regional and global scales. They must be capable of reproducing El Nino, the Earth's diurnal and seasonal cycles, and the inter-annual variability in the climate system. The models must also be capable of reproducing the systematic changes in the radiative energy balance with changing aerosols, water vapor, clouds, and surface properties. Only then can we begin to trust the models to produce accurate global change predictions.

It should be noted that these are not the only tests such models must successfully pass, but they are a critical part of the story. Water and carbon cycles in the climate system are also critical. Moreover, the development, testing, and improvement of such models using global data sets will be an iterative process, with no assurance of success. The process will be a continual narrowing of the uncertainties.

The Earth's climate system, particularly its energy and water cycles, is complex and intricately interlinked. The discovery of these links, and the development of improved predictive computer models using these links, is at the heart of NASA's Earth Observing System (EOS) observations and science plan.

The Terra Spacecraft

Terra is the flagship of the Earth Observing System (EOS), a series of spacecraft to observe the Earth from the unique vantage point of space. Focused on key measurements identified by a consensus of U.S. and international scientists, EOS will enable research on the complex interactions of Earth's land, ocean, air, ice and life systems.

Terra will circle the Earth in an orbit that descends perpendicularly across the equator each day at 10:30 a.m. local time, when cloud cover is at a minimum and the space-based view of the surface is least obstructed. Each individual swath of measurements can be compiled into global images as frequently as every two days. Over a month or more, in combination with measurements from other polar orbiting satellites, Terra measurements will provide accurate monthly-mean climate assessments that can be compared with computer model simulations and predictions.

The Earth Observing System has three major components: the EOS spacecraft, an advanced ground-based computer network for processing, storing, and distributing the resulting data (the EOS Data and Information System); and teams of scientists and applications specialists who will study the data and help users in industry, universities and the public apply it to issues ranging from agriculture to urban planning.

Additional information on NASA's Terra mission can be found on the World Wide Web at http://terra.nasa.gov.