Clouds and the Earth's Radiant Energy System

CERES

NASA's Earth Observing System

Front Cover: *Cloud photo by Art Rangno, University of Washington. Image of the Earth from GOES satellite acquired on August 25, 1992 at 1900 UTC (Hurricane Andrew in the Gulf of Mexico) processed by Fritz Hasler, Goddard Space Flight Center, Laboratory for Atmospheres.*

Back Cover: *Monthly Average all sky and clear sky longwave radiant flux measured by CERES on the Tropical Rainfall Measuring Mission (TRMM) during August 1998. Image processed by Takmeng Wong, Langley Research Center (LaRC).*

CERES

"Man masters nature not by force, but by understanding."

— Jacob Bronowski, 1956

Acknowledgments

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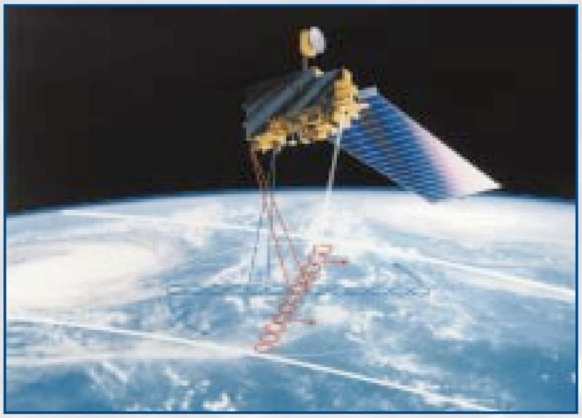


". . . the science of Nature has been already too long made only a work of the brain and the fancy; It is now high time that it should return to the plainness and soundness of observations..."

—Robert Hooke (1635-1703)

NASA's Earth Observing System (EOS) is part of an international program for studying the Earth from space using a multiple-instrument, multiple-satellite approach. This EOS program is critical for improving our scientific understanding of ongoing natural and human-induced global climate change and providing a sound scientific basis for developing global environmental policies.

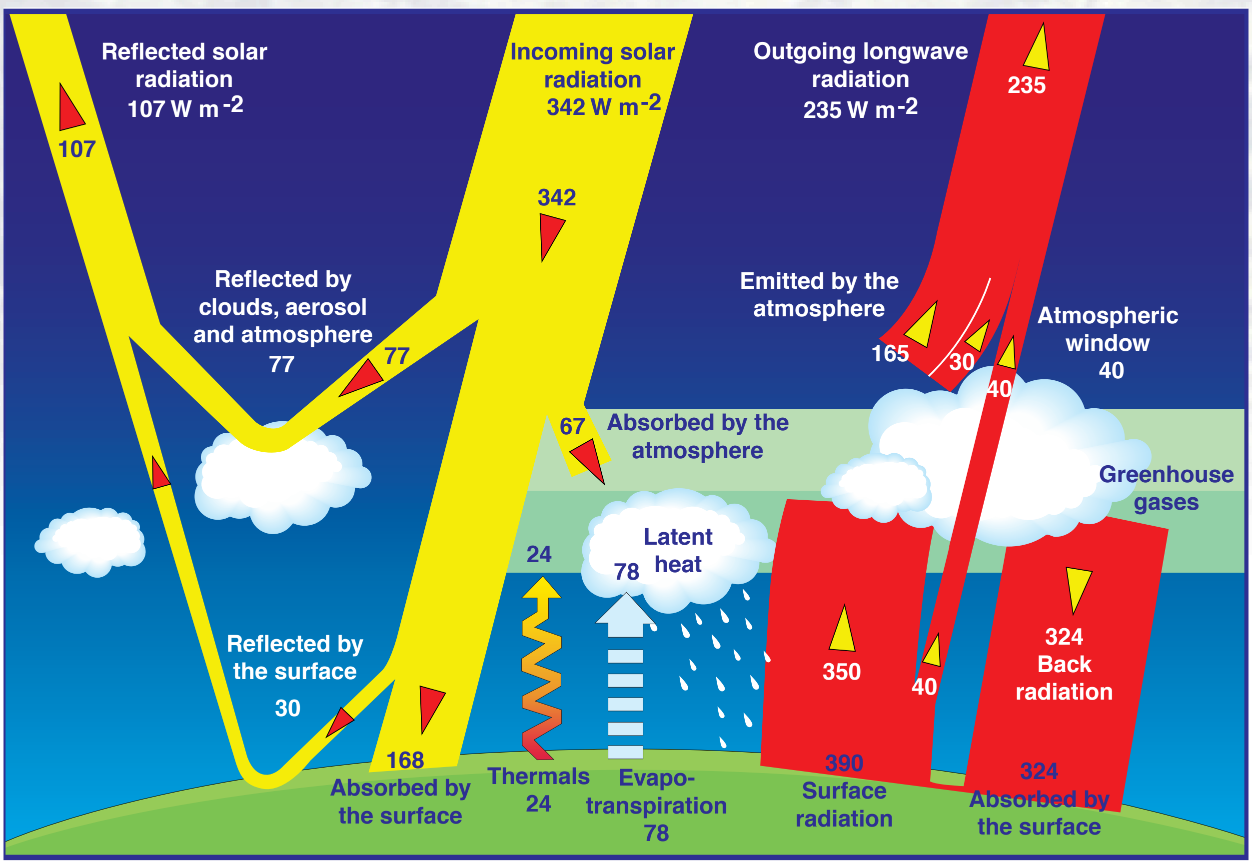
The Clouds and the Earth's Radiant Energy System (CERES) experiment is one of the highest priority scientific satellite instruments developed for EOS. CERES products include both solar-reflected and Earth-emitted radiation from the top of the atmosphere to the Earth's surface. Cloud properties are determined using simultaneous measurements by other EOS instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS). Analyses of the CERES data, which build upon the foundation laid by previous missions such as the Earth Radiation Budget Experiment (ERBE), will lead to a better understanding of the role of clouds and the energy cycle in global climate change.

The first CERES instrument was successfully launched aboard the Tropical Rainfall Measuring Mission (TRMM) satellite in November 1997; CERES will also fly on the EOS satellites starting in 1999. Multiple satellites are needed to provide adequate temporal sampling since clouds and radiative fluxes vary throughout the day. The initial data from CERES on TRMM suggest that the CERES instruments are substantially improved over the ERBE instruments. The CERES data show lower noise, improved ties to the ground calibration in absolute terms, and smaller fields of view. CERES instrument calibration stability on TRMM is better than 0.2% and calibration consistency from ground to space is better than 0.25%. Such levels of accuracy have never before been achieved for radiation budget instruments.

Clouds and the Energy Cycle

The sun's radiant energy is the fuel that drives Earth's climate engine. As shown in the figure, the Earth-atmosphere system constantly tries to maintain a balance between the energy that reaches the Earth from the sun and the energy that flows from Earth back out to space. Energy received from the sun is mostly in the visible (or shortwave) part of the electromagnetic spectrum. About 30% of the solar energy that comes to Earth is reflected back to space. The ratio of reflected-to-incoming energy is called "albedo" from the Latin word meaning whiteness. The solar radiation absorbed by the Earth causes the planet to heat up until it is radiating (or emitting) as much energy back into space as it absorbs from the sun. The Earth's thermal emitted radiation is mostly in the infrared (or longwave) part of the spectrum. The balance between incoming and outgoing energy is called the Earth's radiation budget.

The components of the Earth system that are most important to the radiation budget are the planet's surface, atmosphere, and clouds. Understanding clouds, where they occur, and their characteristics, is thought to be the key to understanding climate change. The effect of clouds on the Earth's radiation balance is measured

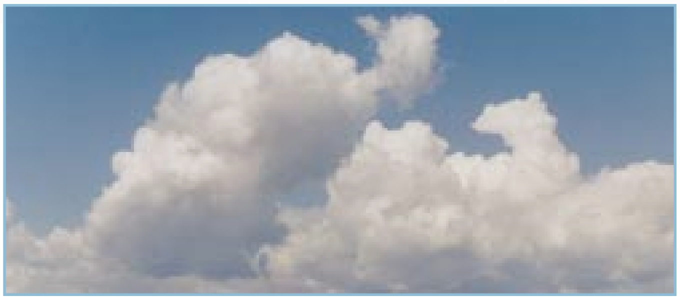


Radiation Balance of the Earth (Jeffrey T. Kiehl) as the difference between the clear-sky and total-scene radiation results. This difference is defined as cloud-radiative forcing. Optically thick clouds reflect more short-wave radiation back to space than the darker surface would in the absence of the cloud. Thus, less solar energy is available to heat the surface and atmosphere which tends to cool the Earth's climate. In addition, roughly 20% of solar radiation is absorbed by atmospheric gases and clouds. The combination of CERES top-of-atmosphere radiation data with surface radiation measurements will allow unprecedented studies of the absorption of solar radiation within the atmosphere. Optical depth is a general measure of the capacity of a cloud or a region of the atmosphere to prevent the passage of light. Greater optical depth means greater blockage of the light and a larger cooling of the Earth-atmosphere system.

Convective clouds (Bruce A. Wielicki)

The intensity of the thermal emission from a cloud varies with its temperature and the optical depth or thickness of the cloud. The top of the cloud is usually colder than the Earth's surface. If a cloud forms in a previously clear sky, the cold cloud top reduces the longwave emission to space, and energy is trapped beneath the cloud top. The trapped energy increases 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 the "greenhouse effect" and, taken by itself, causes a heating of the Earth's climate. High, thin cirrus clouds have a warming effect because they transmit most of the incoming solar radiation while, simultaneously, they absorb some of the Earth's infrared radiation and radiate it back to the surface. Deep convective clouds, such as those associated with thunderstorms, have neither a warming nor a cooling effect because their cloud greenhouse effect, although large, is nearly balanced by the effect due to the convective clouds' high albedo.

Stratocumulus clouds (Bruce A. Wielicki)

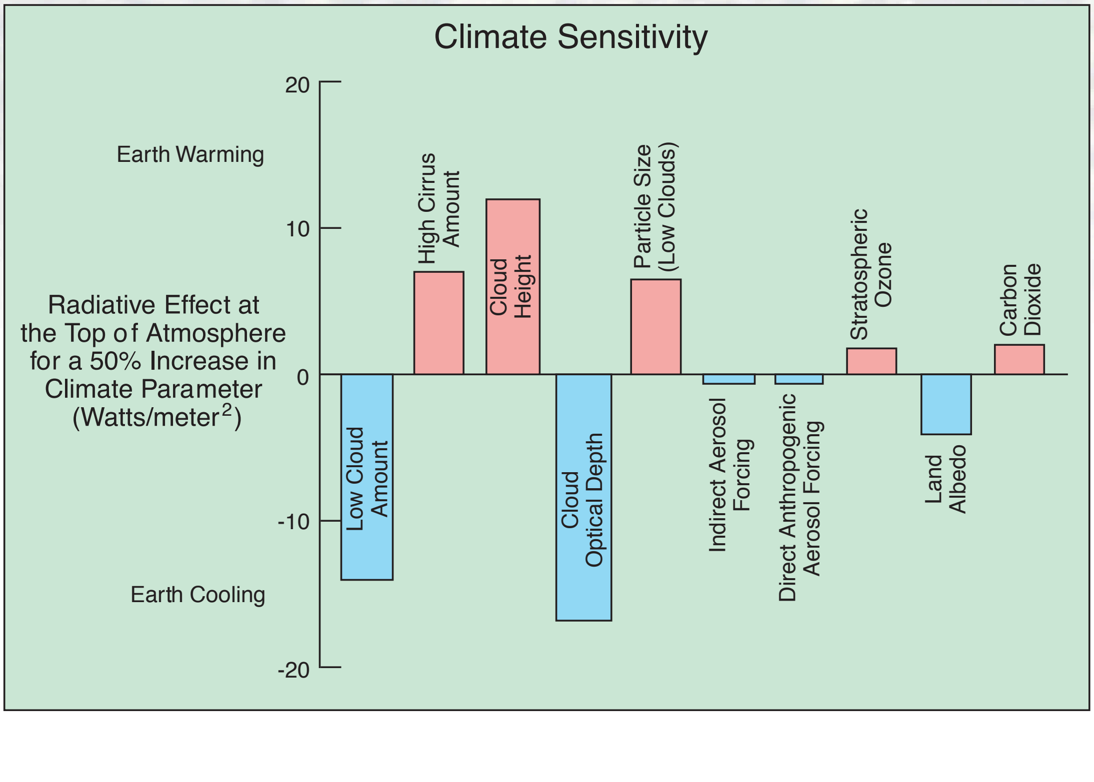


Cumulus clouds (Kevin Larman)

Climate Change and Feedbacks

For centuries, mankind has engaged in activities that alter the environment and, potentially, the global climate. Fossil fuel burning and release of other trace gases and aerosols may well have significant long-term consequences. Since 1800, atmospheric carbon dioxide has increased by 25% and methane concentrations have more than doubled. Agriculture and deforestation alter the Earth's surface in ways that have the potential to change the climate. In these and many other examples, the immediate impacts of man's activities are understood, yet the long-term consequences on the Earth-atmosphere system cannot easily be predicted. For example, one of the major sources of uncertainty in predicting climate change lies in the impact of clouds upon the radiative energy flow through the Earth-atmosphere system. The largest uncertainty in climate prediction models is how to correctly account for the effects of clouds. Because of the importance and uncertainties of clouds and radiation fields, they have become one of the top scientific priorities in the U. S. Global Change Research Program.

As the Earth undergoes changes in its climate, the amount of cloud cover as well as the physical properties of clouds may well change in ways that are not yet understood. The complex interaction between a changing climate system and the changing cloud conditions is called cloud-climate "feedback." Do clouds decrease or increase global warming? Will a warmer climate result in fewer or more clouds? Can a "runaway greenhouse effect" occur as it did on the planet Venus? While we cannot as yet provide definite answers to such questions, the sensitivity results shown below indicate that relatively small changes in global cloudiness can have a large impact on our climate system. For example, a 50% increase in carbon dioxide may warm the Earth much less than a 50% increase in the amount of high cirrus clouds.



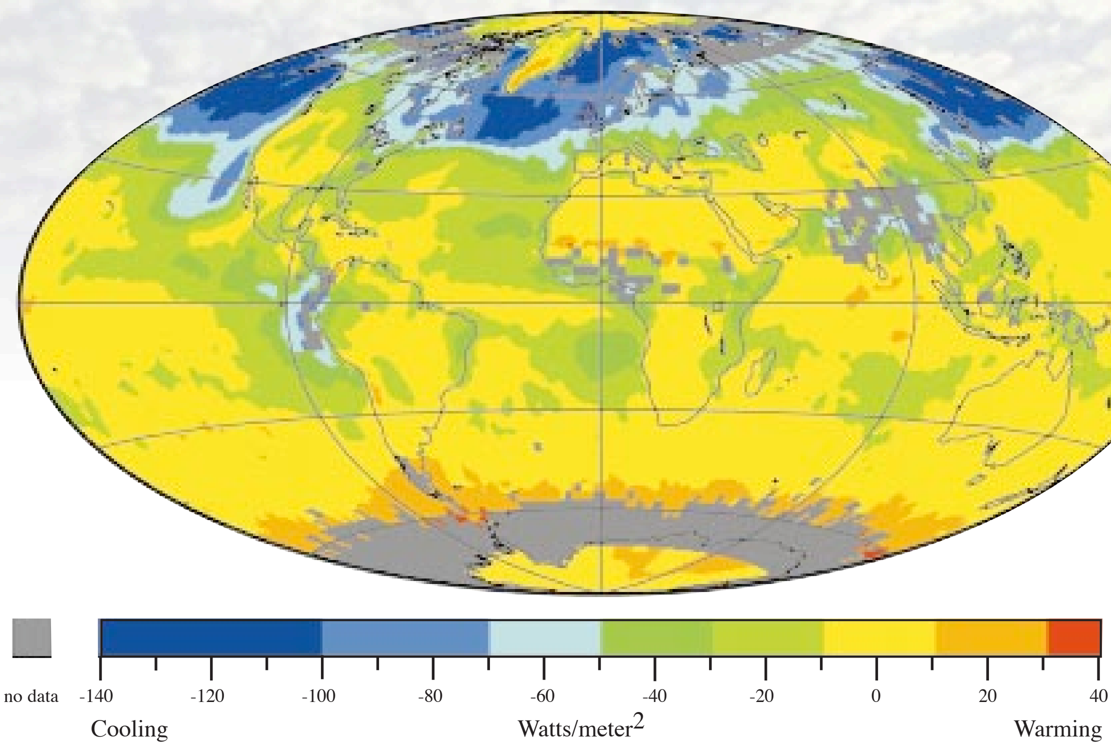
Science Priorities

CERES is focused on four important Earth Science Enterprise priorities for understanding the total Earth system and the effects of natural and human-induced changes on the global environment.

Long-Term Climate Variability

Radiation and clouds strongly influence our weather and climate. For example, low, thick clouds reflect incoming solar radiation back to space causing cooling. High clouds trap outgoing infrared radiation and produce greenhouse warming. The Earth Radiation Budget Experiment (ERBE), which was launched on multiple satellites in the mid 1980s, has provided critical data that indicate that clouds have an overall net cooling effect on the Earth (i.e., negative net cloud forcing in the figure below). The largest negative cloud forcing is found over the storm tracks at high-to-middle latitudes in the summer hemisphere. The most extreme values occur over marine areas, since the contrast in albedo between clear and cloudy conditions is greatest over oceans. In the tropics, the longwave and shortwave cloud forcings nearly cancel; therefore clouds have neither a heating nor cooling effect in these areas. Much more information is needed about clouds and radiation and their role in climate change. The largest uncertainty in climate prediction models is how to determine the radiative and physical properties of clouds. CERES observations will contribute to improving the scientific understanding of the mechanisms and factors that determine long-term climate variations and trends.

Net Cloud Forcing from ERBE
July 1987

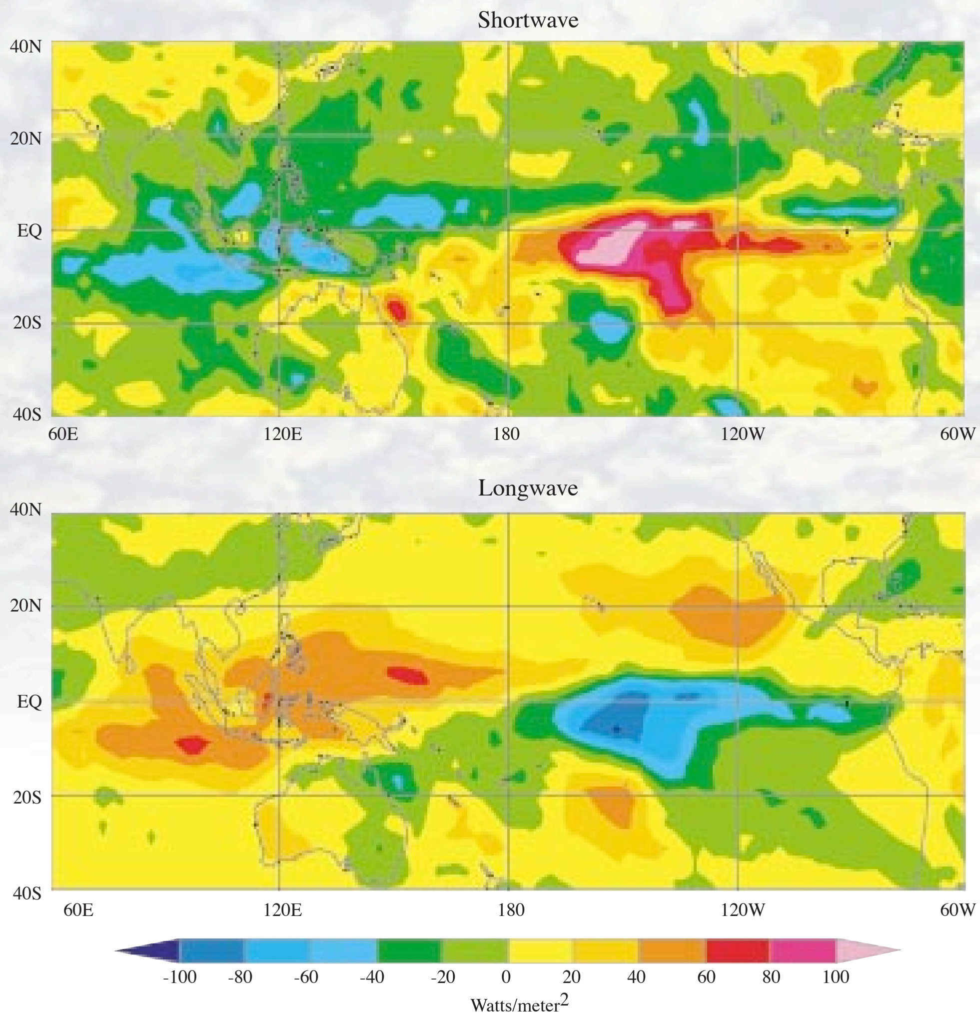


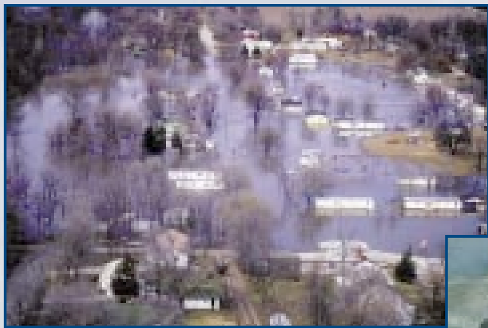
Seasonal-to-Interannual Climate Prediction

Global observations of clouds and radiation provide for better scientific understanding to improve seasonal-to-interannual climate forecasts. For example, early CERES data from TRMM show that the El Niño/Southern Oscillation (ENSO) has a pronounced radiative pattern across the Pacific basin, with increased deep convection in the eastern tropical Pacific and more clear sky conditions in the western tropical Pacific. Strong shortwave and longwave radiative anomalies (i.e., differences from a 5-year average from ERBE) were observed during the latter phase of the 1997-98 ENSO event. The radiative features are closely related to cloud amount, type, and thickness. CERES provides accurate radiation data as well as imager-derived cloud physical and microphysical properties needed to improve our knowledge of such large-scale climate perturbations.

CERES—Derived ENSO Radiative Anomalies

January 1998 Minus January (1985-89)





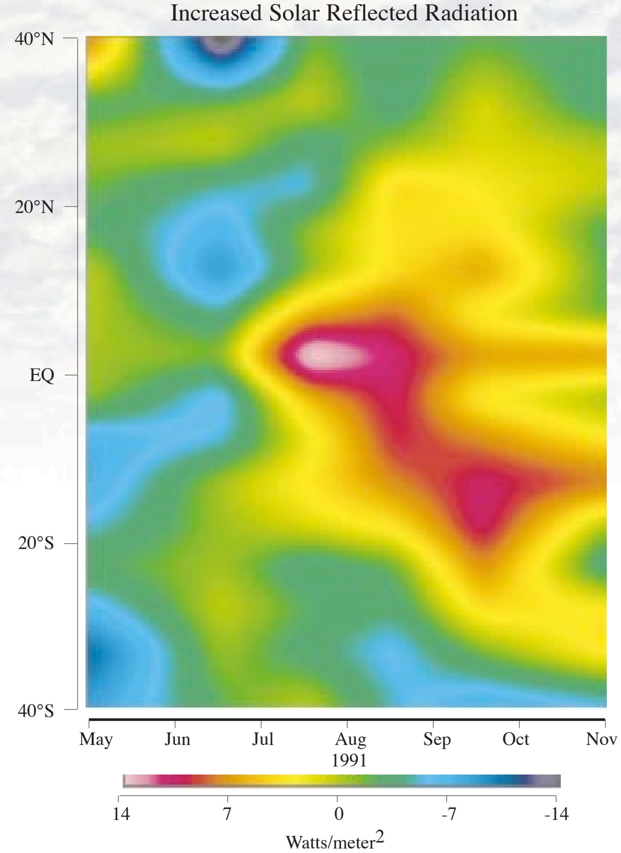
(Yoram Kaufman)

Natural Hazards

CERES provides global data for evaluating the radiative effects and climatic impact of natural events such as volcanic eruptions and major floods and droughts. Volcanic activity has long been suspected of causing significant short-term changes in climate. Powerful volcanic eruptions typically inject huge quantities of gases into the stratosphere, forming an aerosol layer that can remain in the atmosphere for several years. Cooling was so severe following the Tambora eruption in Indonesia that 1816 was called “the year without a summer.” Cold temperatures (snow fell in August) and killing frosts in Europe and America caused extensive crop failures and famine. The 1883 eruption of Krakatoa was heard 3,000 miles away and produced sea waves almost 40 meters high. The vast stratospheric cloud caused such vivid red sunset afterglows that firemen were called out in several cities to quench the apparent conflagration. The volcanic cloud that created such spectacular atmospheric effects also acted as a solar radiation filter, lowering global temperatures as much as 1.2°C in the year after the eruption. Temperatures did not return to normal until 1888.

In 1991, a series of spectacular eruptions of Mount Pinatubo in the Philippines produced the greatest volcanic clouds observed since the beginning of the satellite era. This event presented an unprecedented opportunity for an experiment in climate change. Radiative heat flow (or flux) anomalies derived from ERBE were used to determine the volcanic radiative forcing following the eruption of Mount Pinatubo. Aerosols altered the Earth’s radiation balance by reflecting more of the Sun’s energy back to space as indicated by the yellow and red areas in the shortwave anomaly figure on the right. The Earth continued to cool radiatively at about the same rate as before the eruption. The resulting cooling of

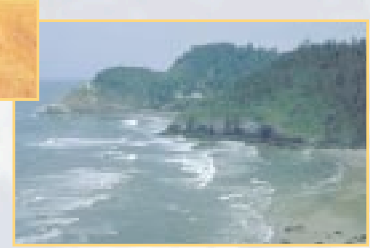
ERBE Observed that Mt. Pinatubo Aerosols Increased Solar Reflected Radiation



the atmosphere and the surface depressed the mean global temperature by some 0.5-1.0°C.

Following any future major volcanic eruption, simultaneous observations of radiation and clouds by CERES and other EOS instruments will yield important new data on how clouds and the climate are affected by the volcanic particles.

(Michael King)

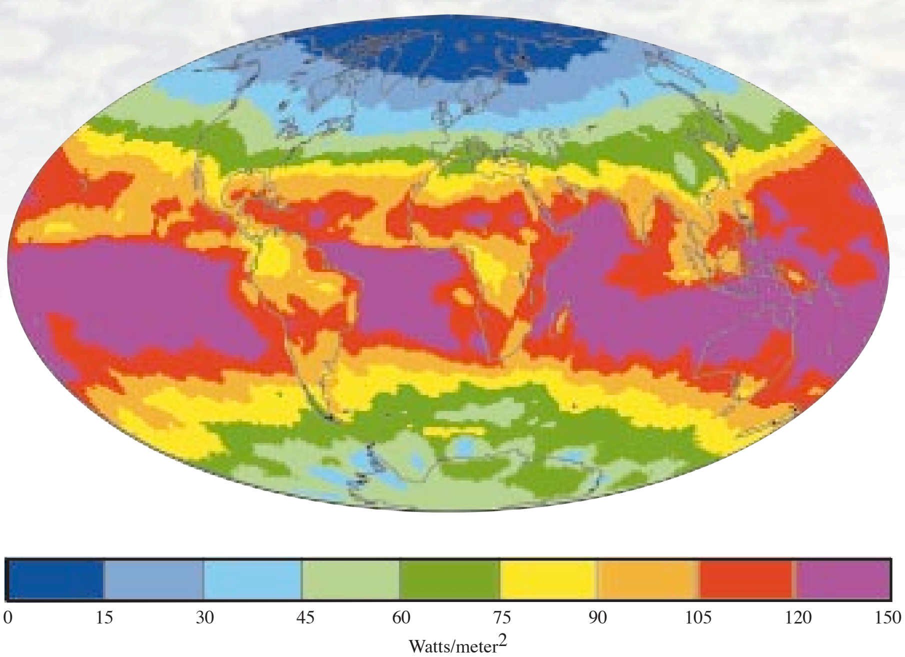


(Michael King)

Land Cover Change and Global Productivity

While satellites measure radiative flux at the top of the atmosphere, most people are more concerned about conditions on the surface where we live, grow our crops, heat and cool our homes, and enjoy our skiing or beach vacations. Consequently, one of the objectives of the CERES investigation is to better estimate radiative fluxes within the atmosphere and at the surface. CERES surface radiation budget (SRB) data help us understand the trends and patterns of changes in regional land cover, biodiversity, and agricultural production. In particular, CERES can detect variations in surface albedo and longwave emission that signal potential changes in the nature of the land, such as desertification. The SRB provides data on solar energy available at the surface, useful for locating sites for solar power facilities and for architectural design applications. The data set also provides estimates of photosynthetically active radiation (as shown in the figure below from the Global Energy and Water-cycle Experiment SRB project) which is important for predicting crop yields.

Photosynthetically Active Radiation (PAR) - October 1986



CERES Objectives

The scientific justification for the CERES measurements can be summarized by three assertions: (1) changes in the radiative energy balance of the Earth-atmosphere system can cause long-term climate changes (e.g., carbon dioxide inducing global warming); (2) besides the systematic diurnal and seasonal cycles of incoming solar energy, changes in cloud properties (amount, height, optical thickness) cause the largest changes of the Earth's radiative energy balance; and (3) cloud physics is one of the weakest components of current climate models used to predict potential global climate change.

CERES has four main objectives:

(1) For climate change analysis, provide a continuation of the ERBE record of radiative fluxes at the top of the atmosphere (TOA), analyzed using the same algorithms that produced the ERBE data.

(2) Double the accuracy of estimates of radiative fluxes at TOA and the Earth's surface.

(3) Provide the first long-term global estimates of the radiative fluxes within the Earth's atmosphere.

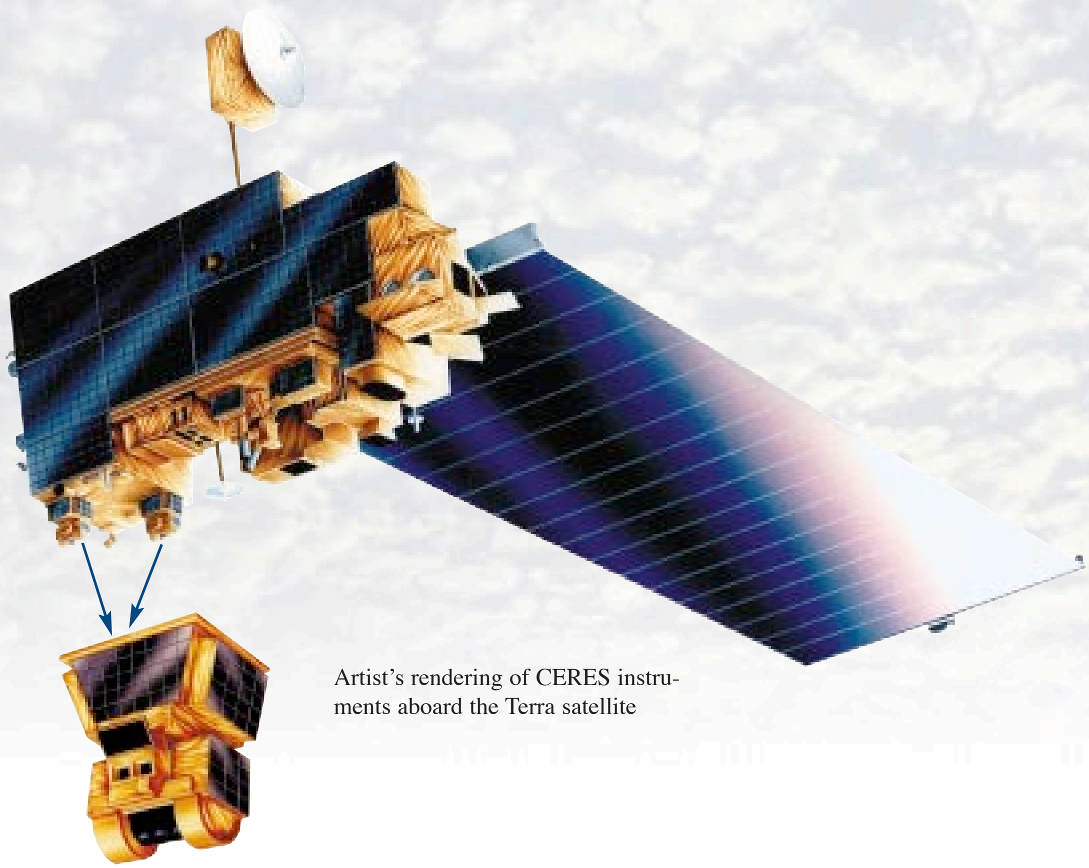
(4) Provide cloud property estimates that are consistent with the radiative fluxes from surface to TOA.

To address the scientific priorities and accomplish these ambitious objectives, stringent accuracy criteria have been established for CERES 1-degree regions as shown in the table below.

CERES TOA Net Flux Error Budget (Watts/meter^2)

Source of Error	Monthly Average Regional 5-yr trend	Monthly Average Regional, 1σ	Daily Average Regional, 1σ
Angular Sampling	0.0	1.2	3.5
Time Sampling	0.0	2.3	8.1
Space Sampling	0.4	0.4	2.0
Instrument Calibration	0.3	1.6	1.6
Total	0.5	3	9
Science Requirement	<1	2 - 5	5 - 10

CERES data and scientific investigations will answer long-standing questions about how to handle clouds in climate models. Follow-up CERES satellite missions are planned to create at least a continuous 15-year history of highly accurate radiation and cloud data for climate analyses. The CERES objectives directly address NASA's Earth Science Enterprise research priorities. CERES data are helping us to understand the trends and patterns of changes in regional land cover, and are providing surface radiation data for solar power, solar cooking, and architectural applications, as well as for the agricultural community. The CERES global observations will provide new data for improving seasonal-to-interannual climate forecasts, including the cloud and radiative aspects of periodic large-scale climate events such as El Niño. CERES data can be used for evaluating the radiative effects and climatic impact of natural disasters such as volcanic eruptions and major floods and droughts. The long-term CERES data set will provide a basis for scientific understanding of the mechanisms and factors such as cloud/climate feedback that determine long-term climate variations and trends. Understanding how clouds influence the Earth's energy balance and the role of clouds in regulating our climate will provide scientists with new insights into developing improved models for forecasting long-term climate. Scientists will be able to investigate on-going natural and human-induced global climate changes. The CERES radiation budget data are also useful for a wide range of other EOS interdisciplinary science investigations including studies of ocean, land, biological, and atmospheric processes.



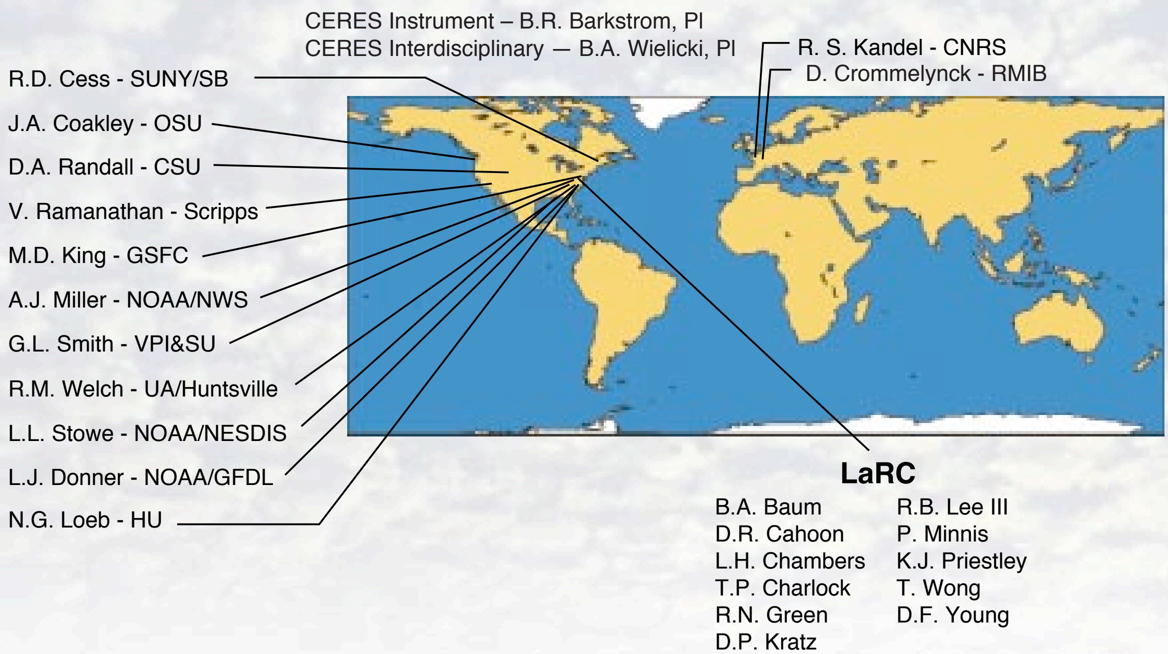
Artist's rendering of CERES instruments aboard the Terra satellite

Science Team

The international CERES Science Team includes scientists from NASA, NOAA, U.S. universities, France, and Belgium. The team blends expertise in broadband radiometry, cloud and radiation remote sensing, and climate modeling. The science team guides the definition of the CERES instrument and science studies. The science team for CERES/EOS is led by an Instrument Principal Investigator (PI) for the instrument, algorithms, and data system, and by an Interdisciplinary Science PI to study the CERES data in conjunction with other EOS data sets and climate models. The team is organized into working groups to focus on five specific aspects of the measurement and analysis problem:

- ◊ Instrument
- ◊ Cloud Properties
- ◊ Top-of-Atmosphere Radiative Flux
- ◊ Surface and Atmospheric Radiation Budget
- ◊ Temporal Interpolation and Spatial Averaging

Clouds and the Earth's Radiant Energy System (CERES) Science Team



SUNY/SB	State University of New York/Stony Brook
OSU	Oregon State University
CSU	Colorado State University
Scripps	Scripps Institution of Oceanography
GSFC	NASA/Goddard Space Flight Center
NOAA/NWS	NOAA/National Weather Service
VPI & SU	Virginia Polytechnic Institute & State University
UA/Huntsville	University of Alabama at Huntsville
NOAA/NESDIS	NOAA/National Environmental Satellite, Data, and Information Service
NOAA/GFDL	NOAA/Geophysical Fluid Dynamics Laboratory
LaRC	NASA/Langley Research Center
CNRS	Centre National de la Recherche Scientifique, France
RMIB	Royal Meteorological Institute, Belgium
HU	Hampton University

CERES Instrument

CERES instrument assembly (TRW)

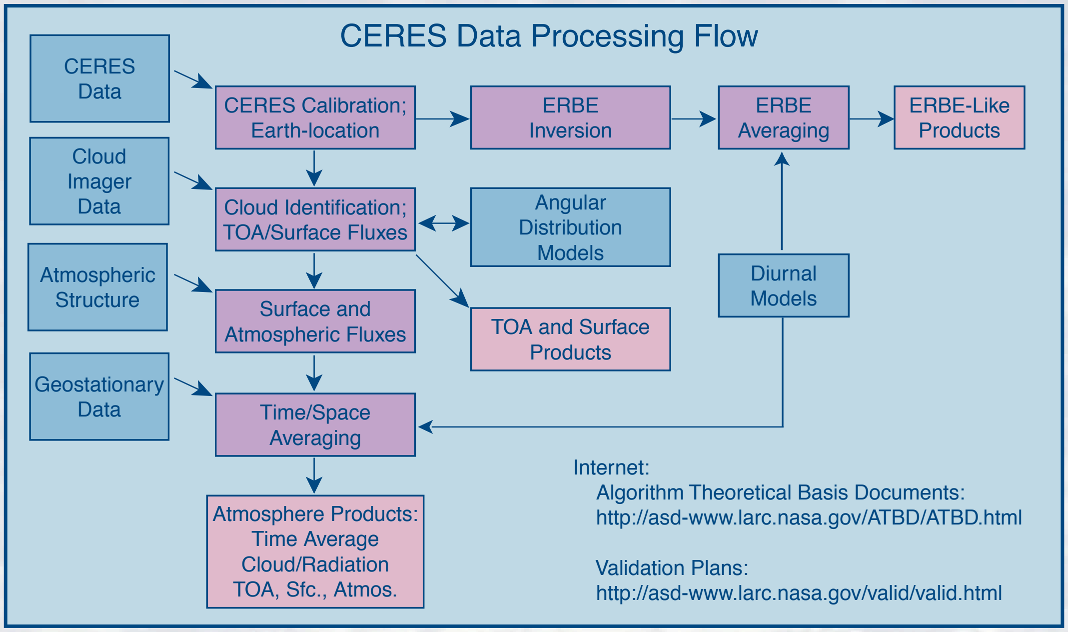
The CERES instrument pictured on the right is based on the successful ERBE scanning radiometer design with several improvements to accommodate upgraded performance requirements and hardware developments. CERES has twice the spatial resolution and improved instrument calibration. The two EOS spacecrafts will each carry two identical instruments: one will operate in a cross-track scan mode and the other in a biaxial scan mode. The cross-track scan will essentially continue the measurements of the ERBE, while the biaxial scan mode will provide new angular flux information that will improve the accuracy of angular models used to derive the Earth's radiation balance.

Each CERES instrument has three channels—-a shortwave channel to measure reflected sunlight, a longwave channel to measure Earth-emitted thermal radiation in the 8-12 µm "window" region, and a total channel to measure all wavelengths of radiation. Onboard calibration sources include a solar diffuser, a tungsten lamp system with a stability monitor, and a pair of blackbodies that can be controlled at different temperatures. Cold space looks and internal calibration are performed during normal Earth scans. During the first year of operation on TRMM, CERES has shown remarkable stability. There has been no discernable change in instrument gain for any channel at the 0.2% level with 95% confidence. Ground and in-space calibrations agree to within 0.25%.

Technical Specifications

Orbits:	705 km altitude, 10:30 a.m. descending node (Terra) or 1:30 p.m. ascending node (PM-1), sun-synchronous, near-polar; 350 km altitude, 35° inclination (TRMM)
Spectral Channels:	Solar Reflected Radiation (Shortwave): 0.3 - 5.0 µm Window: 8 - 12 µm Total: 0.3 to >100 µm
Swath Dimensions:	Limb to limb
Angular Sampling:	Cross-track scan and 360° azimuth biaxial scan
Spatial Resolution:	20 km at nadir (10 km for TRMM)
Mass:	45 kg
Duty Cycle:	100%
Power:	45 W
Data Rate:	10 kbps
Size:	60 x 60 x 70 cm (deployed)
Design Life:	6 years

The CERES instrument is managed by the NASA Langley Research Center in Hampton, Virginia, and built by TRW's Space and Technology Group in Redondo Beach, California.



CERES Standard Data Products

A key element in the success of CERES, beyond the development of an instrument, is the development of data analysis and interpretation techniques for producing radiation and cloud products that meet the scientific objectives of the project. This data analysis yields three major types of archival products. The CERES data product descriptions are given in the Data Products Catalog that can be accessed on the web at http://asd-www.larc.nasa.gov/DPC/DPC.html. CERES TRMM data can be accessed through the Langley Distributed Active Archive Center (DAAC) at http://eosweb.larc.nasa.gov/.

ERBE-like Products are as nearly identical as possible to those produced by the previous generation ERBE instruments. These products include broadband shortwave, longwave, and net radiative fluxes for both cloudy sky and clear sky conditions. ERBE-like products are used for climate monitoring and climate change studies when comparing directly to ERBE data sources.

Top-of-Atmosphere (TOA) and Surface Products use cloud imager data for scene classification and CERES measurements to provide radiative fluxes for both cloudy and clear sky conditions. Surface radiation budget estimates are based on direct observational relationships between top-of-atmosphere and surface fluxes. TOA and surface products are used for studies of land and ocean surface energy budget, as well as climate studies that require high accuracy fluxes.

Atmosphere Products use cloud physical properties, temperature, water vapor, ozone and aerosol data, and a broadband radiative transfer model to compute estimates of shortwave and longwave radiative fluxes at the surface, at levels within the atmosphere, and at the top of the atmosphere. The CERES TOA radiative fluxes are the "truth" reference used to constrain the theoretical calculations. Atmosphere products are designed for studies of energy balance within the atmosphere, as well as climate studies that require consistent cloud, top-of-atmosphere, and surface radiation data sets.

Education and Outreach

The Students' Cloud Observations On-Line (S'COOL) Project is an educational outreach initiative of the CERES experiment. The S'COOL Project was conceived to address a major goal of the Earth Science Strategic Plan: "foster the development of an informed and environmentally aware public." S'COOL students make observations of cloud properties as the CERES satellite passes overhead and forward their data to the NASA Langley DAAC via computer links, FAX, or mail. Students' observations are compared to the satellite-derived cloud properties as part of the CERES data validation effort. Feedback is then provided to the students on how their observations compare to NASA's satellite data. There is no cost to participating schools. In just over 2 years, S'COOL has reached over 250 schools in 21 countries on five continents.

(Carolyn Green)

(Carolyn Green)

(Jeff Caplan)

(Jeff Caplan)

For further information on the CERES instrument and data products see the CERES website at http://asd-www.larc.nasa.gov/ceres/ASDceres.html; send email to: ceres@larc.nasa.gov or contact:

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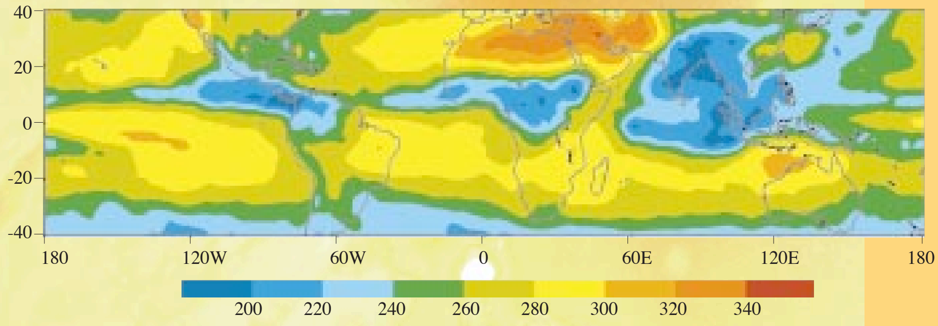
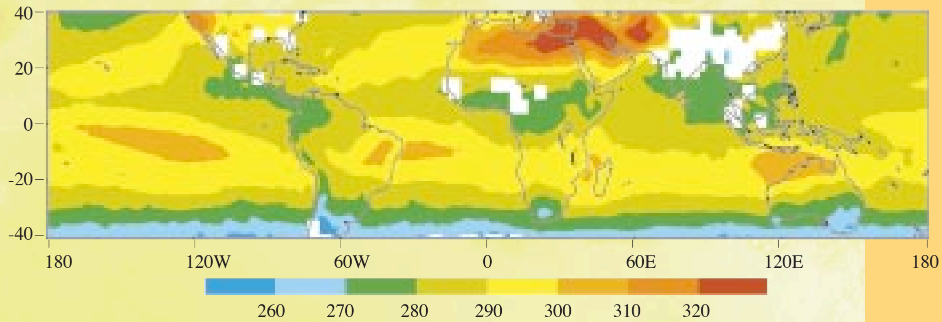
All-Sky Longwave Flux from CERES
August 1998



Clear-Sky Longwave Flux from CERES
August 1998



Watts/meter^2

"Nature is a mutable cloud, which is always and never the same"

—Ralph Waldo Emerson

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