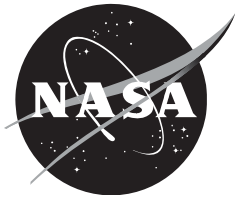


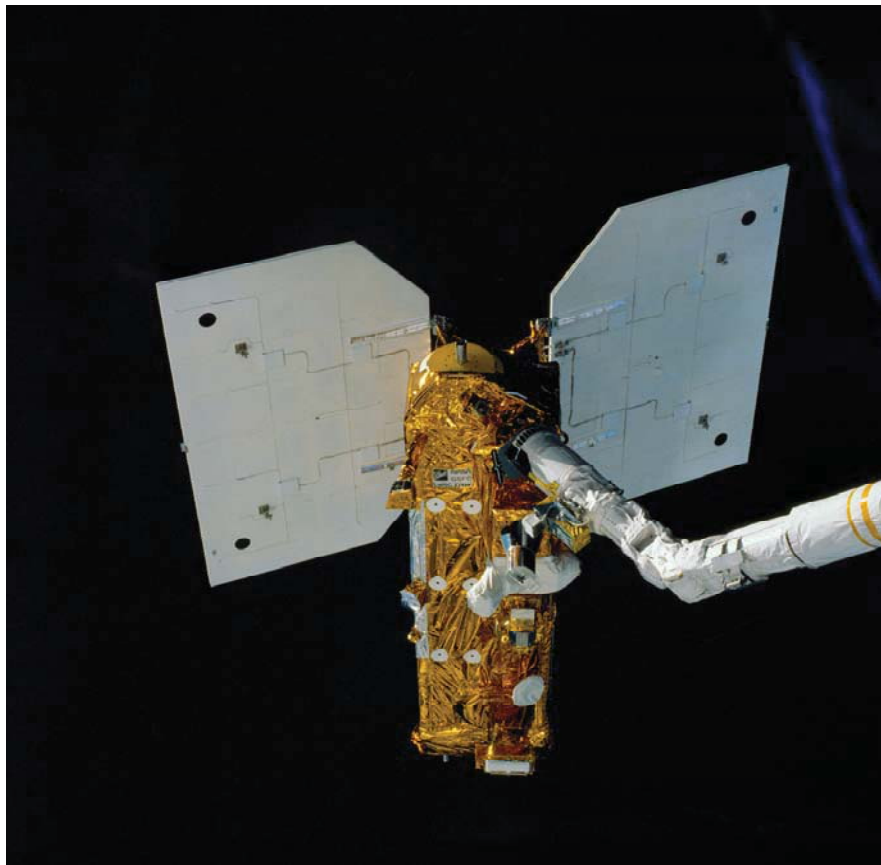
NASA/SP-2014-619



Earth Radiation Budget Research at the NASA Langley Research Center

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Science Systems Applications, Inc., Hampton, Virginia*

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May 2014

Cover: The image on the cover of this publication shows the Earth Radiation Budget Satellite on Remote Manipulator Arm of Space Shuttle Challenger prior to release into orbit.
NASA photograph [STS41G-49-019](#)

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Acknowledgments

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Foreword

In the 1970s research studies concentrating on satellite measurements of Earth's radiation budget started at the NASA Langley Research Center. Since that beginning, considerable effort has been devoted to developing measurement techniques, data analysis methods, and time-space sampling strategies to meet the radiation budget science requirements for climate studies. Implementation and success of the Earth Radiation Budget Experiment (ERBE) and the Clouds and the Earth's Radiant Energy System (CERES) was due to the remarkable teamwork of many engineers, scientists, and data analysts. Data from ERBE have provided a new understanding of the effects of clouds, aerosols, and El Nino/La Nina oscillation on the Earth's radiation. CERES spacecraft instruments have extended the time coverage with high quality climate data records for over a decade. Using ERBE and CERES measurements these teams have created information about radiation at the top of the atmosphere, at the surface, and throughout the atmosphere for a better understanding of our climate. They have also generated surface radiation products for designers of solar power plants and buildings and numerous other applications.

Introduction

In the beginning of space exploration in the early 1960s several research divisions at the NASA Langley Research Center (LaRC) were involved in studying materials in space, instrumented rocket payloads, satellite experiments, and reentry vehicles. These research space flight programs made important contributions to the design of the Apollo heat shield, the lunar orbital rendezvous concept, and lunar landing simulations. Other major space projects in which Langley played a major role in the late 1960s and 1970s included the Viking mission to Mars. Beyond managing a major portion of the Viking project from Earth lift-off to landing on Mars, Langley researchers performed interplanetary trajectory analyses, designed and tested the Mars entry and landing vehicle as well as provided support for instruments, electronics, and systems engineering. The experiences gained in these projects were valuable later in the development of the Earth radiation budget projects at the NASA Langley Research Center. In the mid-1960s the Apollo Program was moving forward; man would set foot on the Moon before the end of the decade. Within LaRC research was being done to send a human to Mars and return to Earth. Research was being done for the design of the heat shield that would protect humans returning from Mars. There were teams in two different organizations of LaRC studying the heating problem. After the successful missions to the Moon, public interest in space exploration waned. In the early 1970s the Nation's interest turned inward and the demand became Relevance and Societal Benefit. At this time, public concern about the environment began to grow. The teams studying reentry from planetary return began looking for ways in which their capabilities could be used to address problems on Earth.

In the late 1950s and early 1960s engineers at NASA Langley were concentrating on various unmanned Earth-orbiting satellites. Engineers under the leadership of William O'Sullivan in the Pilotless Aircraft Research Division (PARAD) developed the technology to place balloons in orbit and inflate them there. The first balloon had a 100-foot diameter (figure 1) and was used to bounce a message from President Eisenhower from Earth to the balloon and back to Earth. This balloon was named Echo and was the first communication satellite. A second balloon with twice the area (140-foot diameter), dubbed Echo II was flown next.

The orbits of these two balloons were perturbed by the thin air through which they flew and by the pressure of sunlight. At that time, little was known about the density of air at spacecraft altitudes, so orbit lifetime estimates had large uncertainties. The perturbations of the orbits of the Echo balloons demonstrated that balloons could be used to investigate the density of air at high altitudes. LaRC engineers had also demonstrated the ability to put a balloon in space and inflate it. A 12-foot balloon (Explorer IX) was placed into a low orbit by a Scout launch vehicle. The Scout was a four stage solid rocket developed at LaRC as an inexpensive booster for placing small satellites into space. Explorer IX was the first payload placed in orbit by Scout, with a perigee of 635 km. and apogee of 2600 km. In 1963 another balloon named Explorer XIX was placed in orbit. The two spacecraft together provided much new additional information about air density at these altitudes.

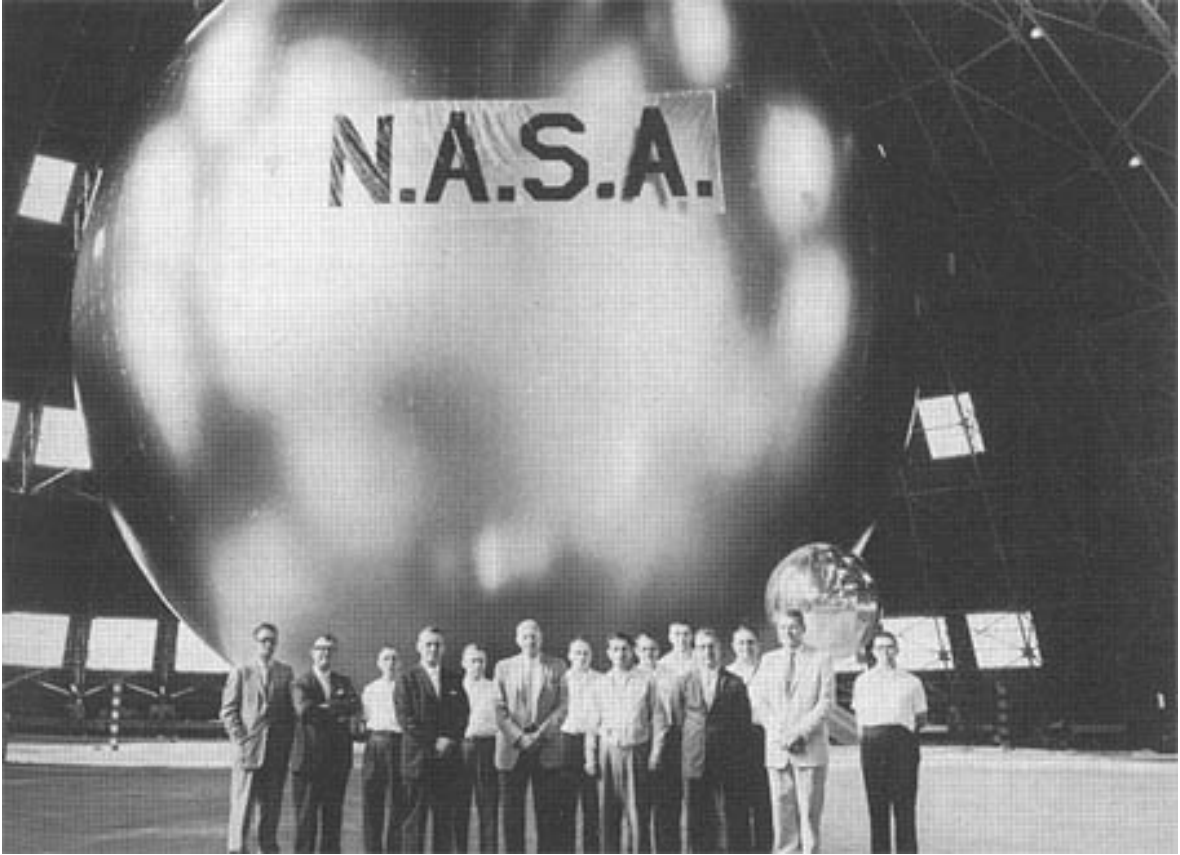


Figure 1: The Echo I balloon in a hanger for development tests, together with the project team.

The Beginning of Earth Radiation Budget Research at Langley



Figure 2: George Sweet, initiator of radiation budget research at the Langley Research Center. Photo Credit of Mrs. Nancy Sweet.

One of the researchers on the team that worked with the Explorer IX and XIX, George E. Sweet (figure 2), pondered what other ways these balloons could be used. The engineers at LaRC knew that the temperature of a balloon depended on the sunlight and Earth-emitted radiation and the color of the balloon's surface. George Sweet reasoned: Let's put three balloons together with three different color coatings and measure their temperatures. From this we can measure the direct sunlight, the sunlight reflected from the Earth and the earth-emitted radiation. This approach applied the concept used by Verner Suomi (figure 3) for the first Earth radiation budget experiment, which was flown on the Explorer VII in 1959 (figure 4).

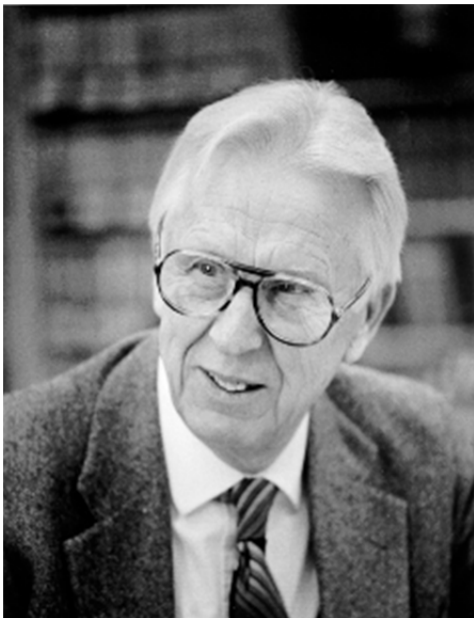


Figure 3: Prof. Verner Suomi. Photo Credit: University Communications, University of Wisconsin-Madison.

Dr. Verner Suomi of the University of Wisconsin had designed an instrument that consisted of two pairs of hemispheres that were mounted on opposite sides of the spinning Explorer IV spacecraft. (Folklore claimed that he used ping pong balls cut in half.) One pair was painted black, the other pair white. The black pair absorbed sunlight, both direct and that reflected from the Earth, and Earth-emitted radiation. The white pair reflected sunlight but absorbed Earth-emitted radiation. Researchers used the temperatures of these hemispheres along with thermal balance equations to calculate the amount of sunlight and Earth-emitted radiation on the device. This experiment provided the first crude measurements of the Earth's radiation balance. For his many contributions, Prof. Suomi is regarded as the father of satellite meteorology.

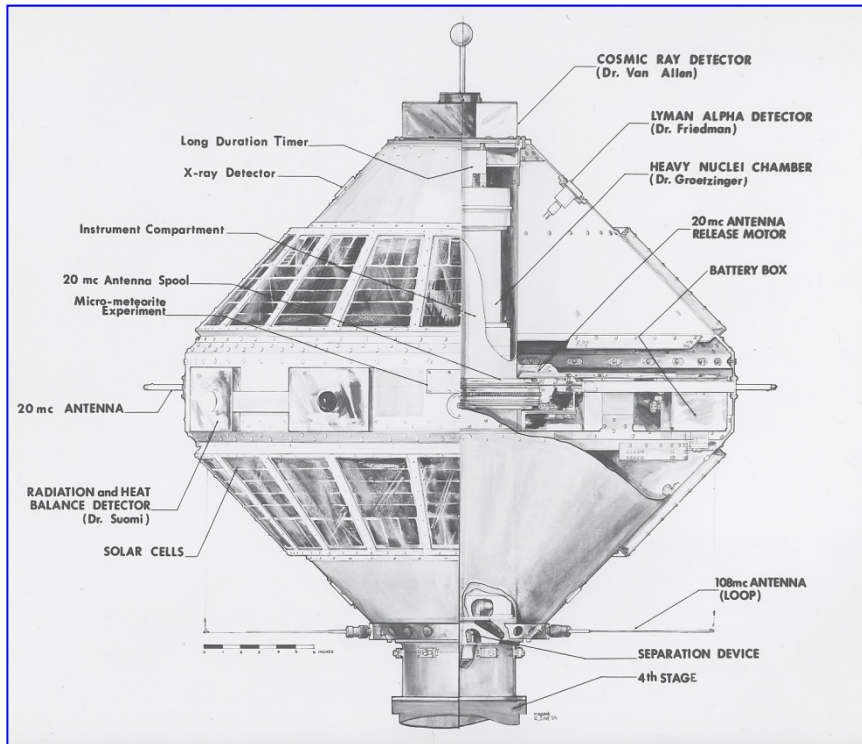


Figure 4: Explorer VII Satellite, with spherical radiometers for measuring radiation from the Earth. Suomi, V. E., 1958: “The radiation balance of the Earth from a satellite,” *Annals of the IGY*, 6, 331-340.

Dr. Suomi was appointed as Director of the Weather Bureau, where he advocated the development of satellite instruments and the application of these measurements to weather forecasting. Dr. Suomi later led the design of the spin-scan instruments and their use on the Geostationary Operational Environmental Satellites (GOES) for continuously observing the weather over the U.S, and the camera that was used on the Viking Lander to give pictures of the surface of Mars in 1976. He returned to the University of Wisconsin, where he founded the Space Science and Engineering Center. As a dominant figure in satellite meteorology, his support for any project to measure Earth radiation budget was vital.

In the early 1970s a team of LaRC engineers from various divisions (Applied Materials and Physics, Aero-Physics, Electronics, and Engineering) was willingly recruited by George Sweet to help develop his concept of using balloons to measure Earth radiation budget. First, the hardware must be designed to achieve the goals of accuracy and longevity. Charles V. Woerner and John (Jack) B. Cooper had also worked on the air density balloon projects and led this effort. Next, methods had to be developed to analyze the data to produce scientifically useful results. George Sweet concentrated on learning the needs of scientists for information about the Earth’s radiation balance. How accurate must the data be? How frequently are measurements needed, daily or monthly? What is the required spatial scale of the measurements, that is, for areas of thousands of kilometers across or only a few kilometers?

While the rest of the Langley Team was working to complete the concept for the experiment, George Sweet began to develop the scientific rationale for measuring Earth Radiation Budget and the requirements for the measurements. George Sweet recruited G. Louis Smith, another engineer in the Applied Materials and Physics Division, and the two visited a number of researchers at the National Center for Atmospheric Research, Colorado State University, University of Wisconsin, and University of Maryland. Their questions were: what would be done with the data when it became available, that is, what scientific questions would it answer, and what were the accuracy and time and space scales required?

What is the radiation budget and why do we need to measure it?

The first question: Why is Earth radiation balance important? The Sun's radiation heats the Earth, making the Tropics hotter than the higher latitudes. These temperature differences cause the atmosphere and oceans to circulate, carrying heat to the cooler regions. The Earth emits heat as radiation, so that the outgoing longwave radiation balances the Sun's radiation. This is illustrated in figure 5. This balance of incoming and outgoing radiation governs our climate. By measuring the terms that balance the budget of radiation over the Earth, we can learn about the climate and the processes that determine the climate. These data would also provide insight into interannual changes of weather and climate, and perhaps lead to the ability to forecast the changes from the average a season in advance. These forecasts would not be specific for a given day, but would apply to the average for the season or month. The measurement of the terms of the radiation budget of the Earth has been an important task in climate research since the earliest days of the Space Age and continues to be so today.

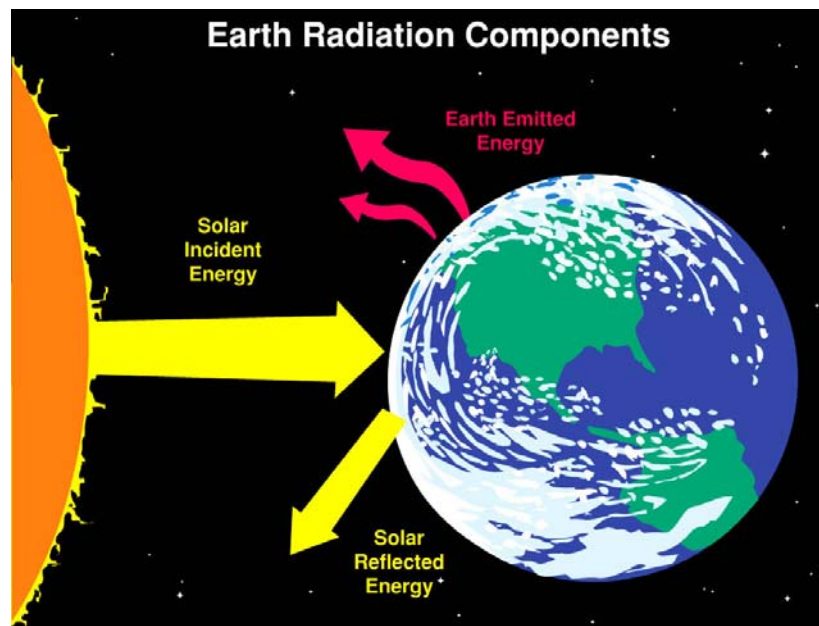


Figure 5: Showing Sun heating Earth, and heat being emitted by Earth.

In the early 1970s, William Bandeen, one of the key people in the early days of Goddard Space Flight Center, brought in Dr. Thomas Vonder Haar, a student of Dr. Suomi, and Dr. Ehrhardt Raschke from the University of Cologne to work with himself and Musa Pasternack, also of GSFC, with data from the Medium Resolution Infrared Radiometer, which had flown aboard the Nimbus-3 research satellite. The Nimbus satellite series, of which there were seven, was a very successful NASA program for developing and demonstrating instruments for observing the Earth, its atmosphere, oceans and ice/snow cover. The work by Bandeen's group demonstrated the ability of satellite instruments to measure the radiation balance of the Earth and the application of this information to studies of the Earth's climate.

At that time, climate models were in their infancy. The prevailing viewpoint was that radiation was important only for time scales of a month or longer. For time scales for weather, the effects of radiation were unimportant and the flow of the atmosphere was dominated by its dynamics. This belief had come about largely because the computer power until then was too limited to include radiative heating and cooling of the atmosphere and the surface. Models of the atmospheric circulation had been developed which excluded radiation and provided reasonable results. The requirement for the resolution of radiation budget data was established as 1 month. Corresponding to the 1-month time scale, the spatial scale was also large. The requirement for the spatial scale for the Langley experiment was taken to be 10-degree zonal averages. The results of the three-balloon design would provide information with zonal resolution, that is, for latitudinal bands, and would operate for a long time because it had no moving parts to fail. For this reason, the concept was named the Long-term Zonal Earth Energy Budget Experiment (LZEEBE; see figure 6).

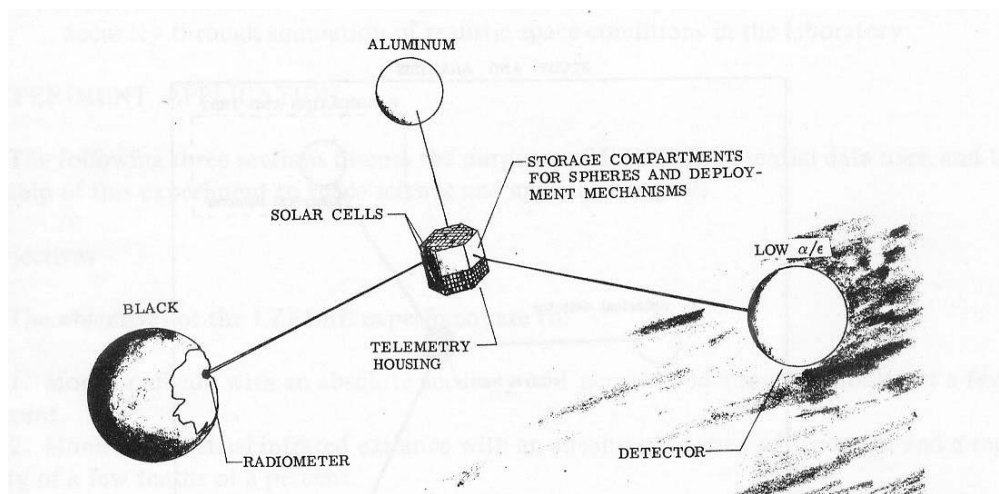


Figure 6: Proposed Long-term Zonal Earth Energy Budget Experiment (LZEEBE).

In order to get a new project start, the LZEBEE concept had to have the backing of the Meteorological Program Office (MPO). This office was a headquarters function, but was located at Goddard Space Flight Center. Funding for NASA, university and industry studies and instrument development came through this Office. The MPO Head was Harry Press, who had come from LaRC where he had worked on the Thunderstorm Project in the late 1940s. Later he moved to GSFC, and served as head of the Nimbus Project. As head of MPO, Harry made certain that if there was a new start for an Earth radiation budget project, it would succeed. The Langley team would periodically go to MPO and present their work. Harry Press would provide his critique and point out the direction in which the team should proceed. He provided the Langley group with a sparring partner to assure that there were no major unresolved problem areas.

Competition Begins

Interest in Earth Radiation Budget was increasing. Professor Verner Suomi had followed his Explorer VII radiation budget measurements with similar radiometers in the ESSA-7 spacecraft. These two spacecraft were also spin-stabilized, with their spin axes perpendicular to their orbits. Professor Suomi proposed to repeat this experiment, but with faster radiometers which would make measurements as they rotated to be horizontal, thus providing a better measurement of flux. Because there were no mechanisms with moving parts to fail, this instrument would operate reliably and provide a long data record. As founder and head of the Space Science and Engineering Center at the University of Wisconsin, he submitted a proposal to NASA to further develop his concept.

Dr. Thomas P. Vonder Haar, at this time at Colorado State University, submitted a proposal to NASA to develop a scanning radiometer to measure Earth's radiation budget. This proposal included participation by Ball Brothers Space Division to develop the engineering aspects of the instrument.

Charlie Woerner and Jack Cooper realized that in order to improve the chances of an eventual radiation budget project, the Suomi and Vonder Haar proposals should proceed through concept definition along with LZEBEE. They subsequently obtained funding through the Meteorology Program Office, which assigned the management of these grants to Langley Research Center. By managing these grants, the Langley team became familiar with each concept and its advantages and disadvantages.

While this work was being done by Langley researchers and through grants and contracts with universities and industry, an Earth radiation budget instrument was being flown by the National Oceanic and Atmospheric Administration (NOAA). Dr. Jay Winston, head of the NOAA Meteorological Satellite Laboratory, insisted that a spatial resolution of 2.5 degrees was required. This spatial resolution requires a scanning radiometer. He had brought Dr. William L. Smith, a recent graduate of the University of Wisconsin and a student of Dr. Suomi, into the Meteorological Satellite Laboratory. Dr. William (Bill)

Smith had developed techniques for using sounding measurements from scanning radiometers to compute temperature and humidity profiles in the atmosphere. Now Bill was developing the Earth Radiation Budget (ERB) instrument (see figure 7), which would fly on the Nimbus-6 and -7 spacecraft. The ERB included a scanning radiometer with eight channels and flat plate radiometers. The scanning radiometer scanned in both the nadir angle and in azimuth, so as to provide measurements that enabled determination of the angular distribution of radiation leaving the Earth's atmosphere. The flat plate radiometers measured solar radiation reflected from the Earth, the radiation emitted by the Earth and the radiation directly from the Sun. After the launch of Nimbus 6, Dr. Smith went on a sabbatical to Australia where he made ground measurements to validate ERB results. Dr. Herbert Jacobowitz, also of the Meteorological Satellite Laboratory, took over the ERB instrument. Unfortunately, the scanning radiometer of the ERB aboard the Nimbus 6 spacecraft only operated for about a month before a cable failure rendered it useless.

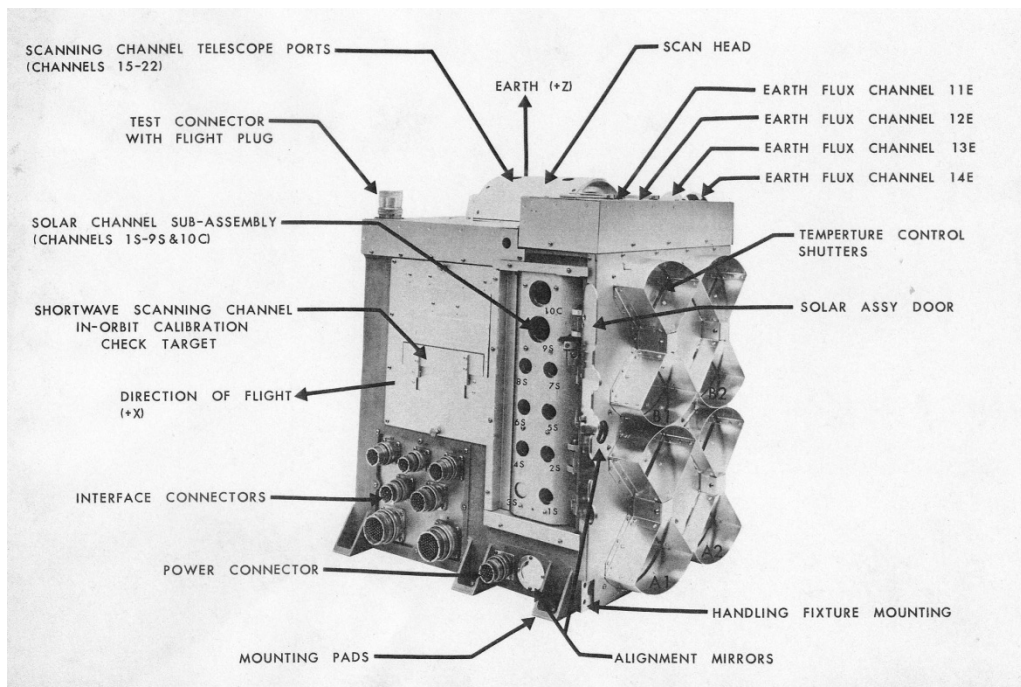


Figure 7: The Earth Radiation Budget instrument. Copies of this instrument flew aboard the Nimbus-6 and -7 spacecraft and provided valuable information for researchers. (W. L. Smith et al., 1977, *Applied Optics*, vol. 15)

However, the wide field-of-view radiometers provided good measurements of the Earth's radiation budget for several years. This early failure of the scanning radiometer added weight to Dr. Suomi's argument that long-term data sets required non-scanning radiometers.

With the Nimbus-7 spacecraft being prepared for launch, NASA began the Science Team concept. Previously, a Principal Investigator (PI) had the responsibility of assuring that the instrument met its scientific objectives and for using the data for scientific investigations. Under the Science Team approach, an Experiment Scientist led a team of scientists in these tasks, which greatly expanded the use of the data for research. NASA sent out an Announcement of Opportunity for participation on the science team for the ERB instrument. The Langley team, headed by Dr. Louis Smith, submitted a proposal for participation on the ERB Science Team, which was accepted. Experience in the ERB Science Team greatly extended the scientific understanding and capability of Langley's team to carry out a project for measuring the Earth's radiation budget.

The Langley team first addressed some key areas for radiation budget measurements required by the scientific community. The determination of the Earth's radiation budget requires several steps, the first of which is the measurements. Robert Babcock, of the Instrument Research Division, studied various radiometer concepts for making these measurements. The measurements are then used to compute the flux "at the top of the atmosphere" at the time of measurement, which requires a model of the distribution of the radiation in all directions. For reflected solar radiation these models are called "bidirectional reflectance distribution functions" because the direction of the incoming and outgoing rays must be included in the computation. Data from the ERB project would be used to generate these models. Richard Green and Lou Smith explored new data analysis techniques.

Space and time sampling was also a key issue. Edwin F. Harrison, head of the Mission Analysis Section of the Space Technology Division and Gary G. Gibson were experts in mission analysis, i.e., the design of orbits for specific purposes. The measurements must cover the entire Earth in order to establish the balance of radiation into and away from the Earth. Finally, the flux must also be known for all times so as to compute the total energy during the day, which also requires information about the variation of fluxes during the day. Patrick Minnis, who had just completed his MS degree in Atmospheric Sciences at Colorado State University, was hired. To get the needed information, Pat went to the World Weather Building of NOAA, where he got daily pictures of satellite imagery. He spent a week with these pictures on a light table, tracing clouds and making estimates of cloud cover as it varied during the day. Although these results could be called subjective, these numbers provided the only knowledge of diurnal variation of radiation at that time. (At that time, computers were not sufficiently advanced to automate this process, but when they progressed to that point, Minnis would use them to do this objectively.) Harrison and Gibson performed computer simulations to determine the geographical and temporal coverage of various satellite orbits for Earth radiation measurements. A satellite must be placed in an orbit that would pass over the Earth at all times of day during a "reasonable" length of time in order to learn how the radiation varies with time of day. Their results indicated that a three-satellite system, including two sun-synchronous satellites along with a mid-inclined orbit satellite, provided the optimal coverage and accuracy for measurement of the Earth's radiation budget. They showed that a satellite placed in orbit by the space shuttle would cover the Earth between 57°N and 57°S

latitude, precess through all times of day during a 72-day period, and provide the data needed to generate the diurnal variation models. To cover the rest of the Earth and to provide additional coverage during the day, instruments should be placed on the NOAA-9 and -10 spacecraft. Figure 8 shows the coverage provided by this combination of instruments. This work placed the Langley team into a position where they understood many of the problems of measuring the radiation budget, analyzing it and producing data that the scientific community could use to improve our understanding of climate.

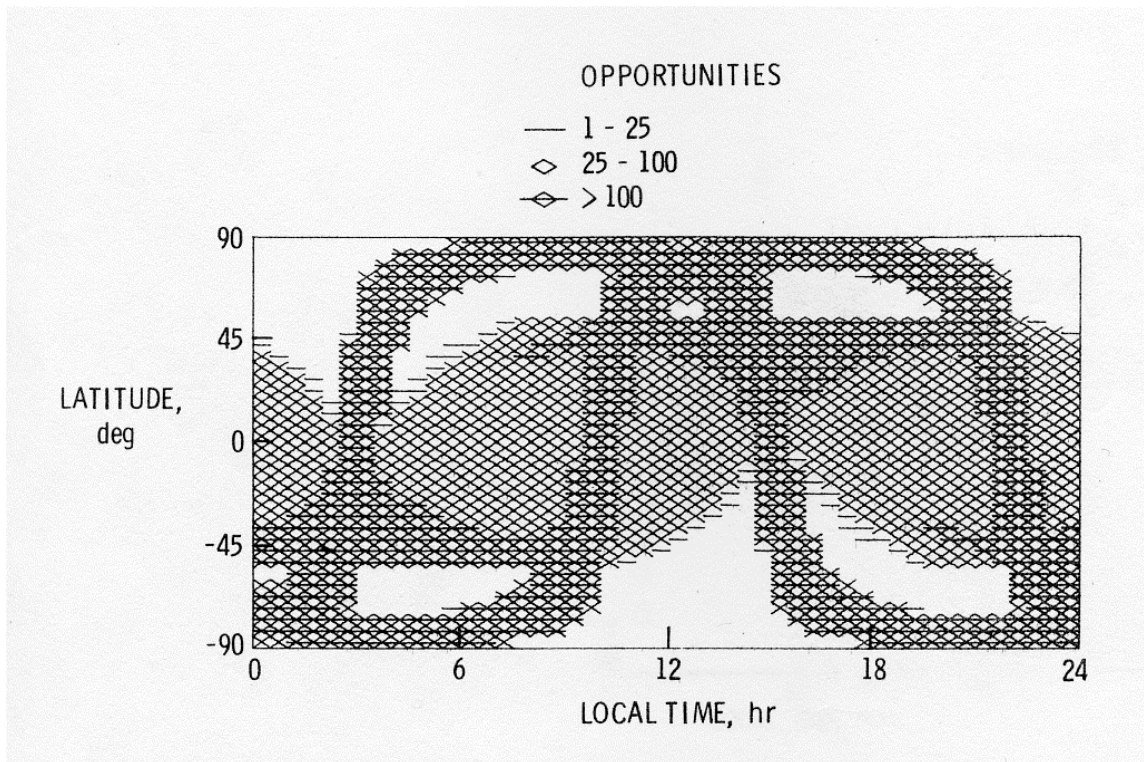


Figure 8: This plot shows the local times when measurements will be made for each latitude by a three-satellite system (Harrison and Gibson, 1981). The band between 60 degrees north and south would be observed by a precessing spacecraft.

The study grants for the concepts of the University of Wisconsin and Colorado State University and the Langley LZEEBE proposal were completed and submitted to NASA Headquarters. Dr. Morris Tepper, Program Scientist for meteorology at NASA Headquarters, was in a dilemma as to what path to take for Earth radiation budget measurements. Professor Suomi, the highly regarded “Father of Satellite Meteorology”, insisted that long-term measurements of Earth radiation budget could only be accomplished by use of flat plate radiometers, which would give a resolution of 10 degrees on the Earth. Because Earth radiation budget is a climate topic, it was necessary to have the support of NOAA before the project would be approved. The head of the Satellite Meteorological Satellite Laboratory, Dr. Jay Winston, insisted on the requirement that any Earth radiation budget program must provide monthly mean maps

with 2.5-degree resolution. This requirement could be met only with a scanning radiometer. The Langley team had stepped into this arena of conflicting requirements and competing organizations. One of our branch heads opined that the Langley team was strong technically but politically inept.

A number of reviews were held of the various concepts, culminating in a review by a panel of the National Academy of Sciences. A Langley team consisting of George Sweet, Louis Smith, Edwin Harrison, Charles Woerner, and Jack Cooper, as well as Robert Curran of Goddard made numerous presentations. After hearing the debate of scientific requirements, resolution and length of time record, the panel concluded that there were two categories of measurements required: one was for a long-term data set that would have a resolution of 10 degrees or smaller, and another was for 2.5-degree resolution data set. The panel endorsed both sets of requirements. Their conclusion was to fly both scanning and flat plate radiometers. In their Special Report of the Atmospheric Sciences Panel of the National Academy of Sciences, 1976, the panel further recommended to NASA that “Langley be asked to analyze the data for the next Earth radiation budget experiments.” The National Academy of Sciences report was a major factor contributing to the decision to assign experiment management responsibility for the NASA Earth Radiation Budget Satellite System to the Langley Research Center.

With the direction provided by the National Academy of Sciences, the Langley team abandoned the LZEEBE concept and developed a proposal to fly scanning radiometers as proposed by CSU and Ball Brothers and also non-scanning radiometer packages. These would fly on the NOAA-9 and -10 spacecraft and a dedicated Earth Radiation Budget Satellite that would be placed into orbit by the Space Shuttle. Although the LZEEBE concept was supplanted by this new approach, it had served the purpose of establishing the science requirements and had resulted in a team that would carry the new project to fruition. This proposal was forwarded by the Meteorological Program Office with its approval to NASA Headquarters. In addition to the National Academy of Sciences recommendation that the Langley Team have the responsibility for the Earth Radiation budget project, Dr. Paul F. Holloway, LaRC Director for Space, attended key reviews and assured NASA Headquarters that the project would have the support of LaRC to make it a success. The project was named the Earth Radiation Budget Experiment to show continuity with the ERB project, and was included in the NASA budget. Congress funded the new ERBE project in the Fiscal Year 1978 budget and also gave NASA the responsibility of conducting research in Earth radiation budget. Langley Research Center now had the responsibility of carrying out this project.

How had this team of retreaded engineers developed a winning proposal and carried out this project to a very successful conclusion? As engineers they each had a solid background in physics and mathematics and the application of these fields. They also built on this background to learn the necessary topics as they went into the new areas. And most importantly, they worked together as a team to accomplish their goal and they were determined to win. Figure 9 shows the Earth Radiation Budget Study Team.



Figure 9: The Earth Radiation Budget study team. Front row: John T. Suttles, Mary Alice Woerner, Lee M. Avis, Richard N. Green. Back Row: Robert Babcock, George Sweet, Charlie Woerner, Louis Smith, Jim Kibler and Edwin Harrison.

The Earth Radiation Budget Experiment (ERBE) Becomes a Project

Given the FY1978 new start, the ERBE Project would design, build, calibrate, and fly scanning and non-scanning instruments on each of three spacecraft, collect and process the data, generate data products, and use them for scientific investigations. The Langley Research Center was given the responsibility for the instruments and the scientific leadership of the project. Goddard Space Flight Center had the responsibility for the Earth Radiation Budget Spacecraft on which the ERBE instruments would fly. At LaRC the project was now organized with the design and building of the instruments in the Projects Directorate and the scientific functions in the Atmospheric and Environmental Sciences Division (AESD) of the LaRC Space Directorate. The scientific functions included collaborating with the project engineering team to specify details of the instrument that affected the measurements and the calibration of the instrument, development of software that would be used for the computations required to process the measurements from electronic signals to useful scientific products, and the use of these products for scientific investigations. Close collaboration was needed between the engineering and scientific teams to assure an instrument that would operate to generate good science data. For ERBE, the years of working together to win the project had made the group a closely-knit, highly collaborative team.

NASA Headquarters also selected LaRC to carry out the Stratospheric Aerosol and Gas Experiment (SAGE). The ERBE/SAGE Project was established within the Projects Directorate of LaRC. Calvin Broom was selected as Project Manager. He was completing his service as Project Manager for the Viking Project, which had orbited two spacecraft around Mars and then sent a craft from each orbiter to land on the Red Planet and make the first scientific measurements from the surface of Mars. Charlie Woerner was assigned as ERBE/SAGE Deputy Project Manager and Jack Cooper as ERBE Experiment Manager. Michael Luther, who had done much of the original work on the LZEEBE concept, was assigned to be Instrument Engineer for the non-scanning package, and Leonard Kopia of the Flight Instrument Division became Instrument Engineer for the scanner. The first task for the engineering team was to write a statement of work, which would be the major part of a Request for Proposals, to design, build, test, calibrate, and deliver three scanning radiometers and three non-scanning radiometers for flight on the Earth Radiation Budget Satellite, NOAA-9 and NOAA-10 spacecraft. Several companies responded to this request and the winning bid was by the TRW Space Division, in Redondo Beach, California. Figure 10 shows the non-scanning radiometer package and the scanning radiometer.

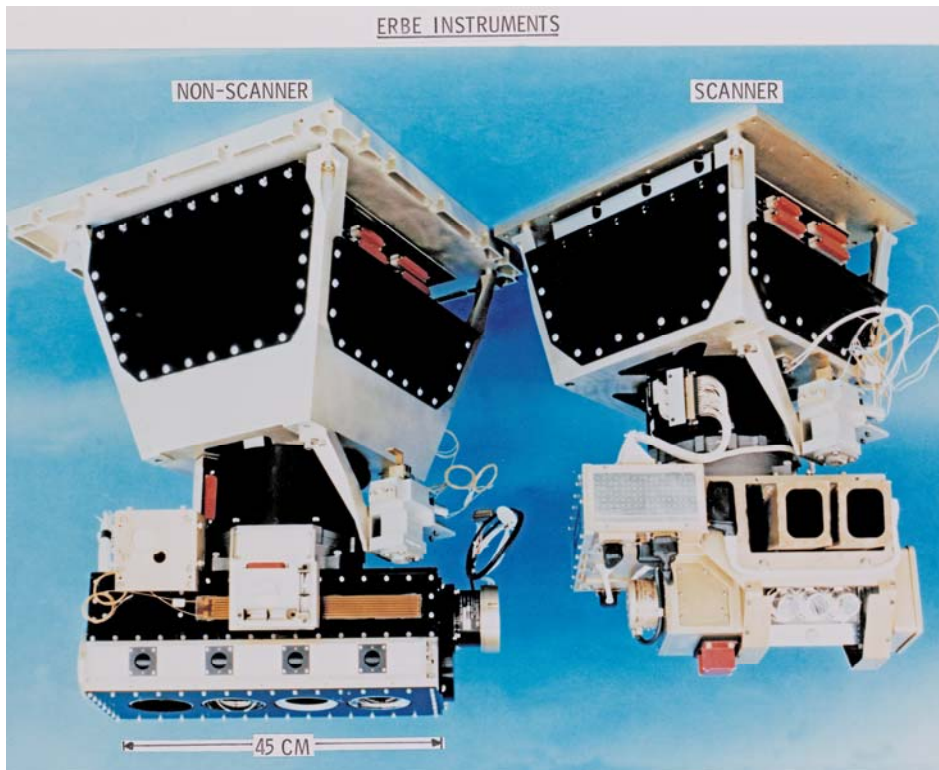


Figure 10: Photograph of the ERBE instruments. The Non-scanning radiometer package is on the left and the scanning radiometer is on the right.

The Radiation Sciences Branch was formed in AESD and included the in-house scientists, with Edwin Harrison as the head. The Data Management Group was formed with the responsibility of producing the software required and using it to process the measurements from the electronic signals from the spacecraft to generate scientifically useful information. James Kibler was selected as head of this group. Kibler had worked from the beginning of the formulation of the project to define the requirements for the data processing. Unfortunately, George Sweet, who had initiated the Earth radiation budget work at Langley died before ERBE got its start.

The first task in AESD was to select an Experiment Scientist, who would have the responsibility for getting the greatest scientific return possible from the project. The Experiment Scientist would lead the Science Team, coordinate with the engineering team in the design of the instruments, manage the development of the software to process the data, and defend the budget for the science work in the Byzantine politics of a major project. Dr. Bruce Barkstrom, a professor with George Washington University and an expert in radiative transfer theory, was selected for this role. His first task was to work with the team in AESD to specify instrument requirements for the Statement of Work being prepared by the engineering team. Next, he wrote requirements for the Announcement of Opportunity for participation on the ERBE Science Team. An international team was selected from the researchers responding to this announcement, including scientists from universities and research laboratories across the US and in Europe. Table 1 lists these ERBE Science Team and their affiliations. This core team along with several other researchers (Figure 11) were involved in preparing the project and the application of the data for scientific investigations.

The Science Team was organized into four working groups, with responsibilities for the instrument, the computation of fluxes at the “top of the atmosphere,” the averaging of the fluxes at the times of measurement to produce daily mean fluxes, and finally to define the data products needed by the scientists. In-house scientists had been working already in the first three areas and continued this work throughout the project. Lee Avis worked on many details of the instrument requirements to use in the Statement of Work. Richard Green and Lou Smith worked on methods of retrieving the “top of atmosphere” (TOA) fluxes from the measurements from the scanning and non-scanning radiometers (Figure 10). For the scanning radiometer, based on the approach used by Raschke, Vonder Haar et al. Green and Smith developed new methods of retrieving TOA fluxes from the non-scanner measurements. Tim Suttles led a team that used data from the ERB instrument and radiative transfer theory to create the bidirectional reflectance functions that were needed for retrieving the TOA fluxes. Suttles’ work in angular modeling was incorporated in his dissertation for his Ph. D. from Old Dominion University. These models would be used for the ERBE, the European Scanner for Radiation Budget (ScaRaB), and the ERBE follow-on project called CERES (Clouds and the Earth’s Radiant Energy System). These angular models were superseded more than two decades later by models developed by Dr. Norman Loeb using CERES data. David Brooks and Edwin Harrison developed methods for using the instantaneous measurements to compute daily-mean fluxes.

Table 1: ERBE Science Team Principal Investigators.

Investigator	Institution	Investigator	Institution
Bruce Barkstrom	LaRC	Gary Hunt	University College
Andre Berrior	CNES	Herb Jacobowitz	NOAA/NESDIS
Robert Cess	SUNY/Stony Brook	Robert Kandel	Ecole Polytechnique
James Coakley, Jr.	Oregon State U.	Ann Mecherikunnel	GSFC
Charlie Duncan	GSFC	A. J. Miller	NOAA/NMC
Yves Fouquart	U. de Lille	V. Ramanathan	U. Chicago
Arnold Gruber	NOAA/NESDIS	Ehrhard Raschke	U. Koeln
Edwin Harrison	LaRC	Louis Smith	LaRC
Dennis Hartmann	U. Washington	W. L. Smith	U. Wisconsin
Fred House	Drexel University	Tom Vonder Haar	Colorado State U.
Fred Huck	LaRC		

Other Science Team Members

Robert Schiffer	NASA/HQ	ERBE Program Manager
Robert Curran	GSFC	ERBE Project Scientist
Michael King	GSFC	ERBE Project Scientist

Abbreviations in Tables

LaRC	Langley Research Center
CNES	Centre National d'Etudes Spatiales
SUNY	State University of New York
GSFC	Goddard Space Flight Center
NOAA/NESDIS	National Oceanic and Atmospheric Administration/National Environmental Satellite Data and Information Service
NOAA/NMC	National Oceanic and Atmospheric Administration/National Meteorological Center



Figure 11: ERBE Science Team at Science Team Meeting at LaRC.

As the time approached for launching the Earth Radiation Budget Satellite (ERBS) and the NOAA-9 spacecraft, Thomas Charlock, Patrick Minnis and Bruce Wielicki were brought into the team to provide science expertise. Minnis and Harrison used Geostationary Operational Environmental Satellite (GOES) data to establish the half-sine shape for the diurnal variation of outgoing longwave radiation. Bruce Wielicki and Richard Green developed the scene identification algorithm for selecting the bidirectional reflectance distribution functions for retrieving TOA fluxes from the measured radiances. Charlock, an expert in climate modeling, focused on making sure that ERBE data products addressed the needs of the modeling community. Shortly after the first ERBE launch, Robert B. Lee III joined the team to lead the Instrument Working Group.

ERBE Goes into Orbit

In order to measure the Earth's radiation budget for all hours of the day, Edwin Harrison and his colleagues had shown that a minimum of three spacecraft would be needed. ERBE instruments would fly on two of the Sun-synchronous operational spacecraft that NOAA uses to observe and measure the atmosphere and oceans. The third spacecraft (ERBS) was built primarily to carry ERBE instruments. It also carried the SAGE as a "guest instrument". Figure 12 is a drawing of the ERBS, showing the ERBE scanning and non-scanning instruments, the SAGE instrument and the major parts of the spacecraft. The spacecraft was built by Ball Aerospace Systems Division.

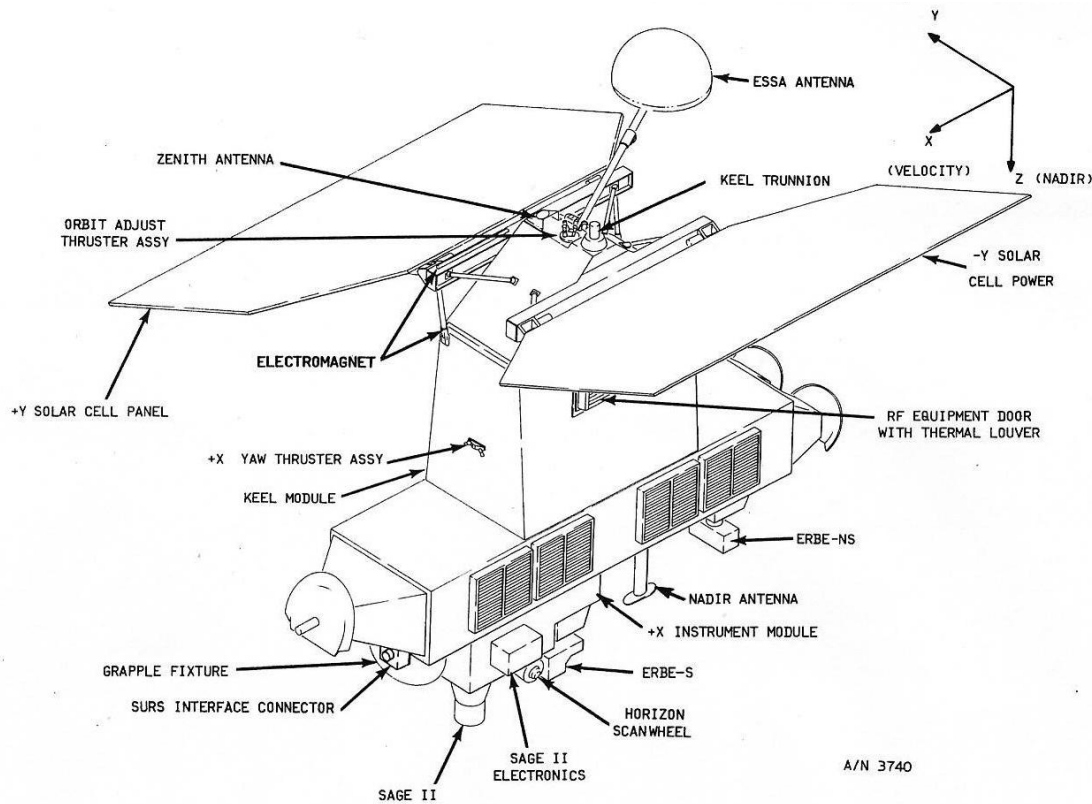


Figure 12: Earth Radiation Budget Satellite configuration in orbit.

ERBS was boosted into orbit by the Challenger Space Shuttle in October, 1984 and deployed by astronaut Dr. Sally Ride, who was Mission Specialist for Flight 41-G. In order to deploy the spacecraft it was necessary to grip the spacecraft using the Shuttle arm (Remote Manipulator System), release the spacecraft from its cradle in the Shuttle bay and move it out into space. The solar cell arrays provided electrical power to all systems of the spacecraft and were folded in order to fit into the Shuttle bay. Before releasing the spacecraft these arrays must be unfolded and locked into place. Initially, the arrays were stuck and would not unfold. If they did not unfold, the mission would be a failure. Dr. Ride used the procedures that had been prescribed for this contingency. First she shook the spacecraft. No luck. Last chance was to wait until the Shuttle had been in the shadow of the night side of Earth and everything cooled down in the darkness of space, and when the Shuttle emerged into daylight and the Sun warmed all of the parts, shake well. This worked. (Standard practice of any auto mechanic to break loose a recalcitrant bolt: heat it then turn it.) The solar arrays opened and locked into place, to the relief of all involved. All spacecraft and instrument systems were checked out and operated well. ERBS was now ready to fly.

After this mission, Dr. Ride served at NASA Headquarters on several major tasks, then in 1989 became a professor of physics at University of California/San Diego and Director of the California Space Institute. In 2001 she founded Sally Ride Science, a company to motivate girls and young women to pursue science careers.

Challenger placed the ERBS into a low Earth orbit. ERBS then fired its own rocket motor to boost itself into an orbit 620 km above Earth, where it would begin observing the Earth's radiation budget and stratospheric ozone and aerosols. A month was allowed for the gases from the rocket engine and any other contaminants from the spacecraft to disperse completely, then the contamination covers to the instruments were opened and the measurements of the Earth began. The scanning radiometer had been designed with a goal of 2 years of operation. It provided measurements for 5 years. The non-scanning radiometer measured the Earth's radiation for 15 years. In October 1999, there was a problem in which the detectors did not return to their correct position after a calibration check, but stuck in a tilted position. They continued to provide data for another 5 years, for a total of 20 years of measurements.

The Earth Radiation Budget Satellite performed extremely well over the entire period. Also, the Flight Operations Team at the Goddard Space Flight Center kept the spacecraft operating as desired during this time. They solved problems in real time, such as loss of a gyro, so that no data were lost. Their performance over two decades was outstanding. It is necessary to leave sufficient spacecraft capacity to maintain control until it is deboosted from orbit, to eliminate space debris. In October 2004, the instruments were turned off and the spacecraft was idled.

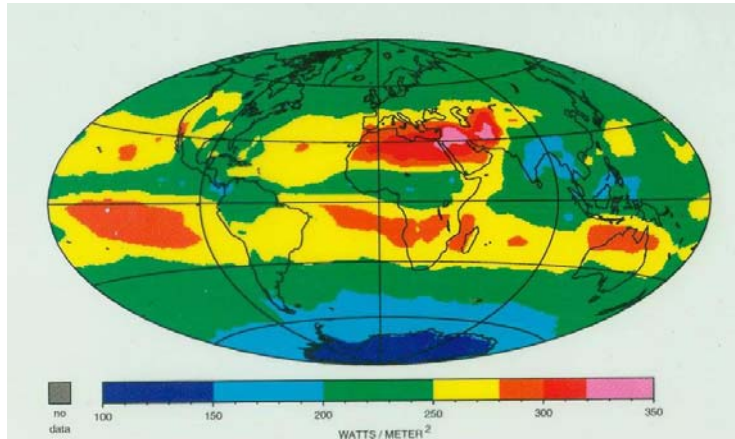
To provide observations at high latitudes, ERBE scanning and non-scanning packages were included in the NOAA-9 and -10 operational meteorological spacecraft. The

NOAA-9 was launched from Vandenberg Air Force Base in December 1984. The ERBE contamination covers were opened in January 1985 and ERBE was now giving global coverage of radiation budget data. Its orbit crossed the Equator (north bound) at 1430 hours initially. Two years later NOAA-10 was placed into orbit, with an orbit crossing the Equator at 1930 hours initially. The system of instruments on three spacecraft needed for sufficient coverage in time and space was now complete.

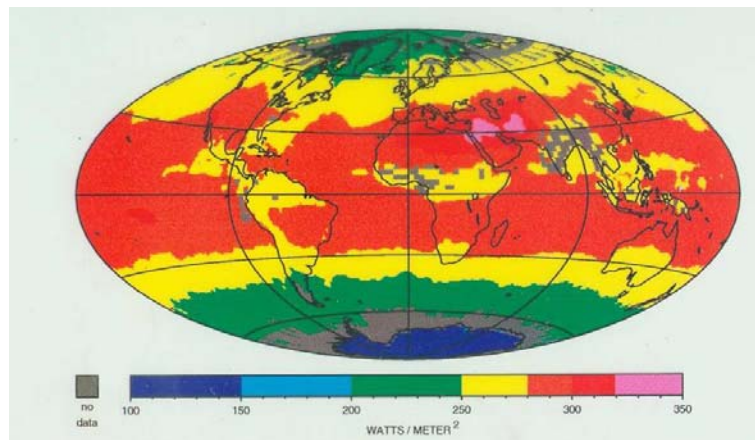
ERBE Accomplishments

The ERBE project archived over five years of ERBS scanner data, two years of scanner results from NOAA-9, and over two years of data from NOAA-10. Over 200 peer-reviewed journal articles have been written that use ERBE data. These papers included the effects of clouds on the balance of Earth's energy, the effects of a volcanic eruption on the climate, the variation of energy absorbed from the Sun and given off by the Earth during the day, and the energy given off by the Sun over a 15-year period. Here we discuss only a few highlights of the research to date using ERBE data.

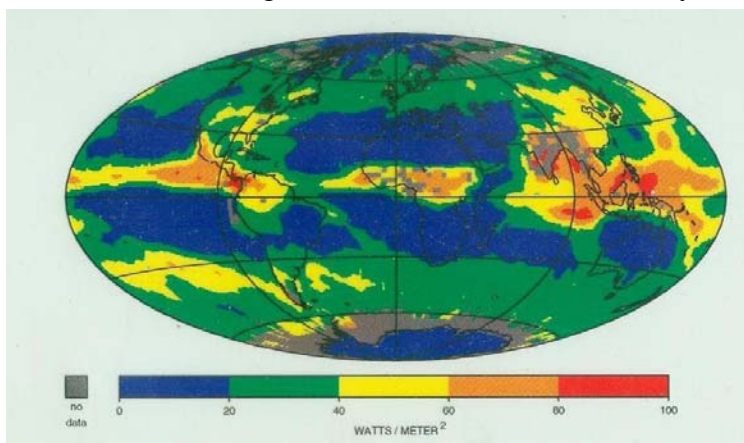
The Importance of Clouds and their Effects: ERBE results demonstrated that the effects of clouds on the radiation balance of Earth were the greatest uncertainty in global climate models. The most important achievement of the Earth Radiation Budget Experiment was the first accurate measurement that proved that clouds cool the Earth. There is no way for the Earth to respond to the energy arriving as light from the Sun and absorbed by the planet except by reemitting light to the coldness of outer space. Hot surfaces, like the Sahara Desert or Death Valley, California, emit a lot of heat. Cold surfaces, like Antarctica or a snow field, emit relatively little heat. The Earth's temperature is established by balancing the energy absorbed from the Sun against the energy the Earth emits back to space. Before ERBE, scientists were not sure whether the increased reflection from clouds would offset the effect that clouds have in trapping the emitted heat. By increasing the amount of energy reflected back to space, clouds decrease the energy absorbed from the Sun. However, clouds also trap the energy emitted by the Earth's surface. High clouds are particularly effective at trapping emitted heat. The ERBE instruments were able to measure the radiation budget of both clear and cloudy areas. Figure 13a shows the longwave radiation emitted by Earth for all sky conditions. Fig. 13b shows the longwave radiation flux emit by the Earth when skies are clear. The difference is the effect of clouds on longwave radiation, which is called cloud radiative forcing (fig. 13c). Similar maps can be made of shortwave radiation showing the effects of clouds on radiation reflected by the Earth with and without clouds, to get the shortwave cloud forcing. The difference between the shortwave and longwave cloud forcing is the total cloud radiative forcing and is shown in figure 14. The scientists on the ERBE science team were able to show that low clouds reflect more energy than high clouds trap. In other words, clouds cool the present climate.



a. Longwave radiation flux for all-sky condition for July 1985



b. Longwave radiation flux for clear sky



c. Cloud forcing of Longwave radiation flux for July 1985.

Figure 13: Maps of longwave radiation fluxes for July 1985. a) As measured for all sky conditions, b) as measured for clear sky, i.e. no clouds and c) difference between the two, which is cloud forcing of longwave radiation.

With ERBE providing quantitative information about the effects of clouds on the solar radiation absorbed by the Earth and the radiation emitted by Earth, scientists were able to check their circulation models to find how well these numerical models simulated the effects seen by ERBE. Figure 15 shows a comparison of ERBE results for net radiative forcing of clouds with that computed by a model used by Tom Charlock and V. Ramanathan (University of Chicago) and by Bob Cess (SUNY/Stony Brook) and Jerry Potter (Lawrence Livermore National Laboratory) for the month of January. While the models have the correct overall shape, there are features that indicate areas to be improved.

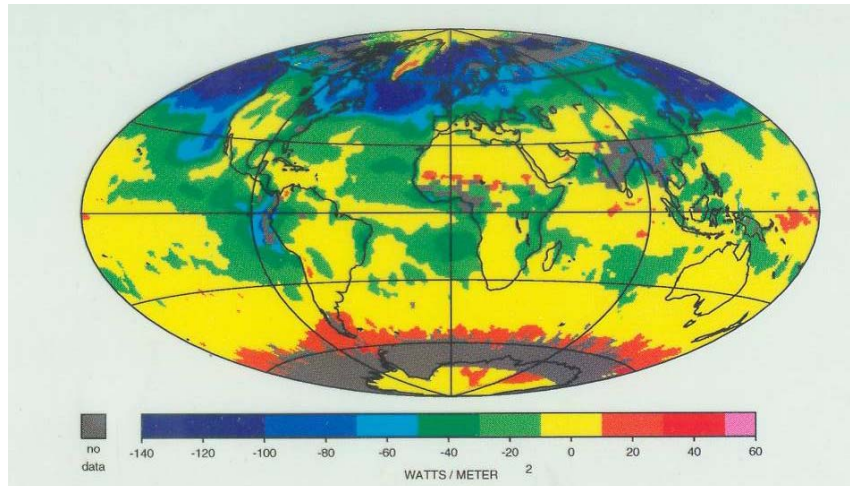


Figure 14: Net cloud forcing of radiation for July 1985 as determined from ERBE data.

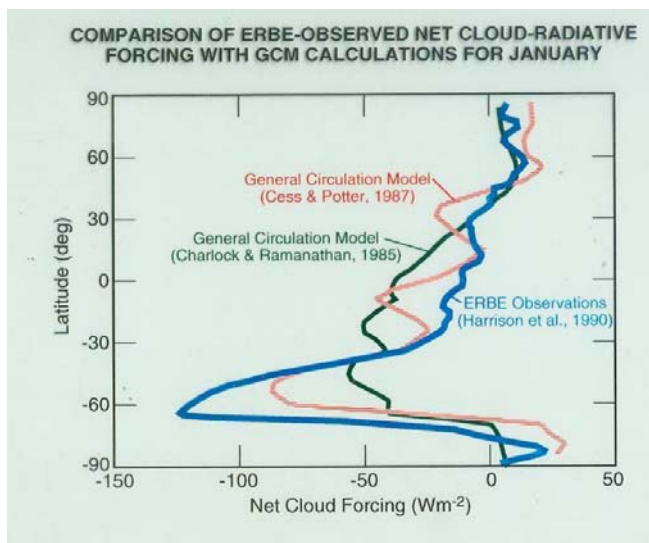


Figure 15: Comparison of Cloud –Radiative Forcing observed by ERBE (Blue line) with general circulation model calculations. Black line: Charlock and Ramanathan (1985); Red line: Cess and Potter (1987).

Cess and Potter collaborated with 19 modeling groups around the world to compare their model results with ERBE observations. These groups included the National Center for Environmental Prediction NCEP (U. S.), the United Kingdom Meteorological Office UKMO, Max Planck Institute MPI (Germany), and the Geophysical Fluid Dynamics Laboratory GFDL (U. S.). Figure 16 shows some of their results. The first plot shows the biases, or average differences, for the cloud forcings at the TOA between the general circulation models and those observed by ERBE. The second part of figure 16 shows the biases due to shortwave and longwave separately. The last part of figure 16 shows the annual net radiation averaged over the Earth. Without global warming, this number should be zero, but is believed to be between $0.5-0.7 \text{ W-m}^{-2}$ due to global warming. These results on cloud radiative effects have enabled scientists to improve their models.

The Daily Cycle of Radiation: The reason for instruments on multiple spacecraft was that the variation during the day of outgoing longwave radiation and reflected solar radiation was unknown. If there are no clouds, the surface heats up during the day, the outgoing longwave radiation (OLR) increases and during evening and night the surface cools and the OLR decreases. However, if clouds develop in the afternoon, the cold cloud tops will radiate less OLR to space. A study by the team showed the change during the day of OLR. Figure 17 shows the variation of OLR during the day in April for a point in South America. The dotted line shows the OLR for clear sky and the solid line shows the average OLR for all cases. The OLR changes during the day over a range of about 30 W-m^{-2} for this location. Figure 18 is a map of the ranges of OLR over the Earth. The deserts have very large changes of OLR during the day because with little or no vegetation they have very large temperature increases during the day and cool to low temperatures at night. Vegetated areas have much lower ranges of OLR. For ocean, there is very little change in temperature during the day because oceans can store a tremendous amount of energy with very small increase of temperature.

The above discoveries led to the declaration of the role of clouds as the top scientific priority of the U.S. Global Change Research Program.

Effects of Volcanoes on Climate: In addition to this fundamental measurement of the impact of clouds, ERBE was able to show the effects of a volcanic eruption on Earth's climate. Mount Pinatubo, in the Philippines, erupted in June 1991 as shown by fig. 19. Tiny stratospheric droplets formed from the volcanic cloud of dust and gases sent into the stratosphere when the volcano erupted. Sunlight changes the gas to tiny droplets of sulfuric acid that we see as the red color of twilight. The droplets grew by absorbing water from the stratosphere and then settled into the lower layers of the atmosphere over a 2-year period after the eruption. The ERBE instruments measured the increase in reflected sunlight as the cloud spread north and south, as shown by figure 20. Figure 21 shows the reduction of reflected sunlight when averaged over the globe. The average reflected sunlight was increased by over 4 W-m^{-2} . The outgoing longwave radiation also decreased by over 1 W-m^{-2} as shown in figure 21. The decrease of OLR reduced the net effect of cooling due to the reflected shortwave radiation, so the net result was a cooling as shown also by figure 21.

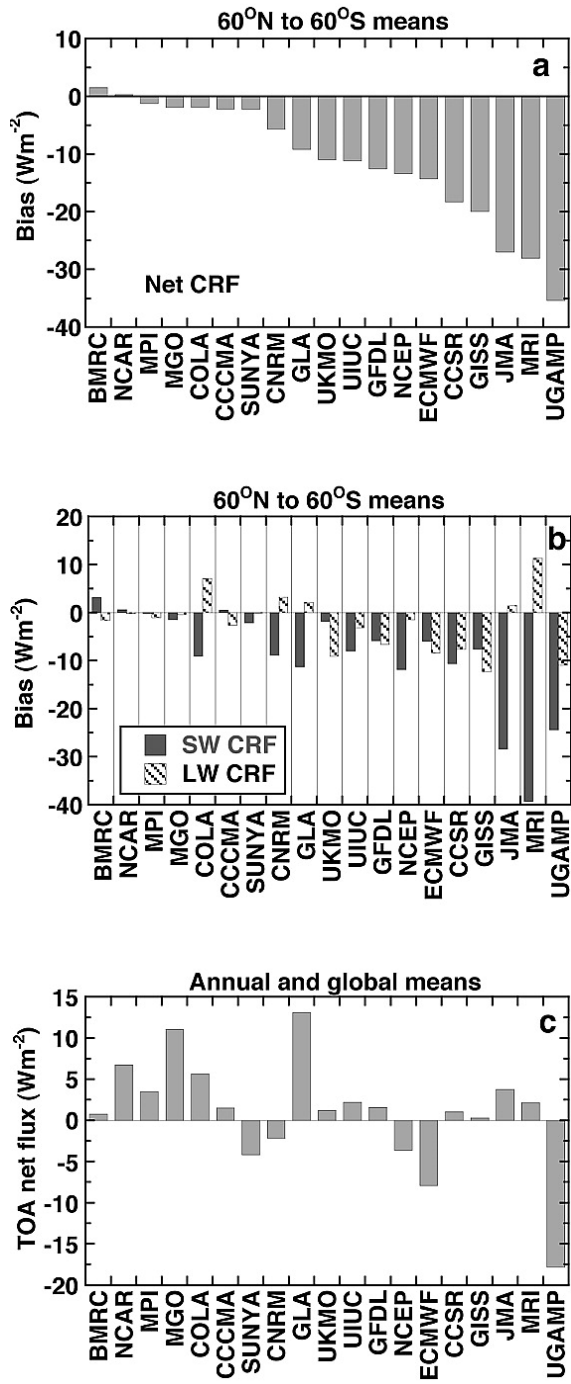


Figure 16: a. Difference of cloud forcing between each of 19 general circulation models and observations from ERBE, averaged over Earth between 60o south and 60o north; b. Same as a, but for shortwave and longwave separated; c. Net radiation over the Earth as computed by 19 general circulation models. (G. L. Potter and R. D. Cess, 2004: *J. Geophys.Res.*, 109, D02106)

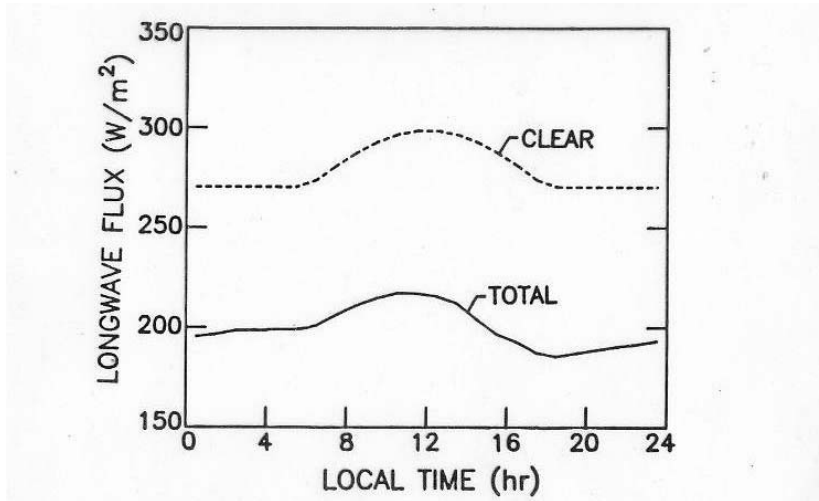


Figure 17: Change of outgoing longwave radiation during day in April 1985 for region 3.75°S, 66.25°S. The dotted line is for clear sky and solid line is the average for all conditions. (Harrison et al., Oct. 1988, *Bull. American Met. Soc.*, 69)

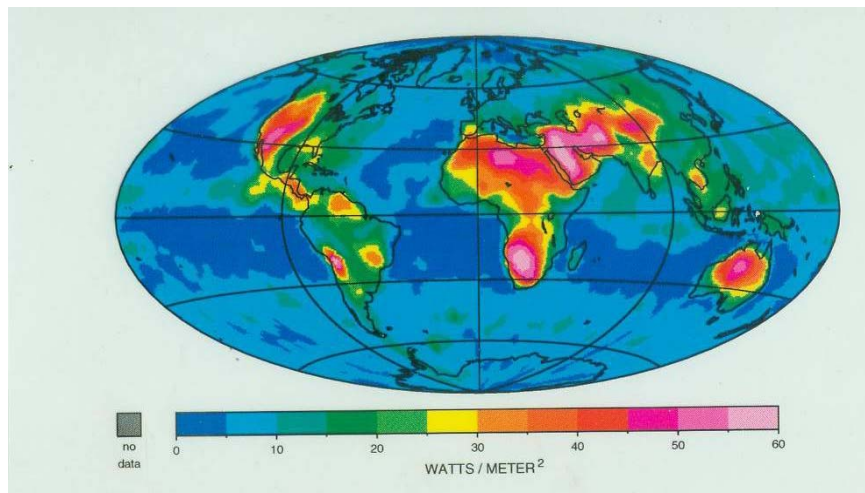


Figure 18: Range of change of Outgoing Longwave Radiation for April 1985. (Harrison et al., Oct. 1988, *Bull. American Met. Soc.*, 69)



Figure 19: Mount Pinatubo erupted in June 1991, sending vast amounts of volcanic aerosols into the stratosphere. (USGS, <http://pubs.usgs.gov/fs/1997/fs113-97/>)

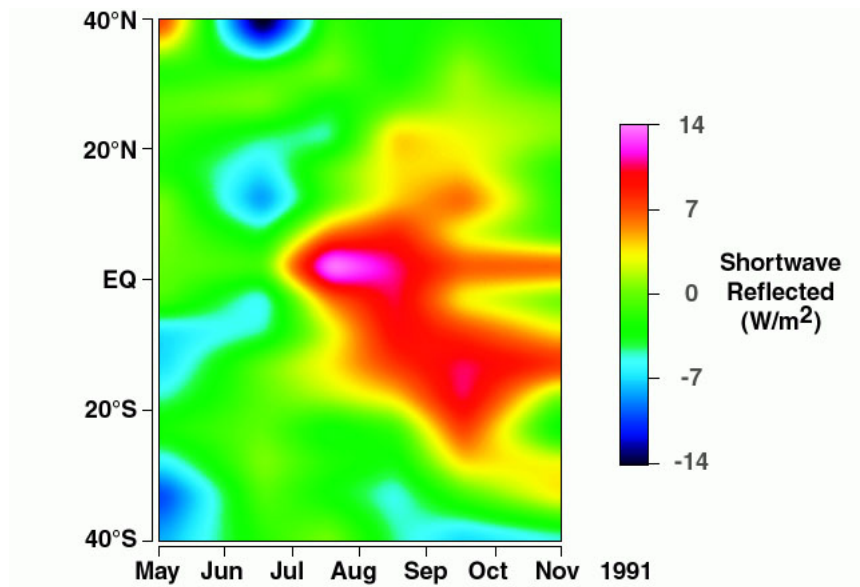


Figure 20: ERBE showed that the aerosols in the stratosphere from the Mount Pinatubo eruption increased the reflected sunlight, thus cooling the Earth. (Minnis et al., *Science*, 5 March, 1993, v. 259)

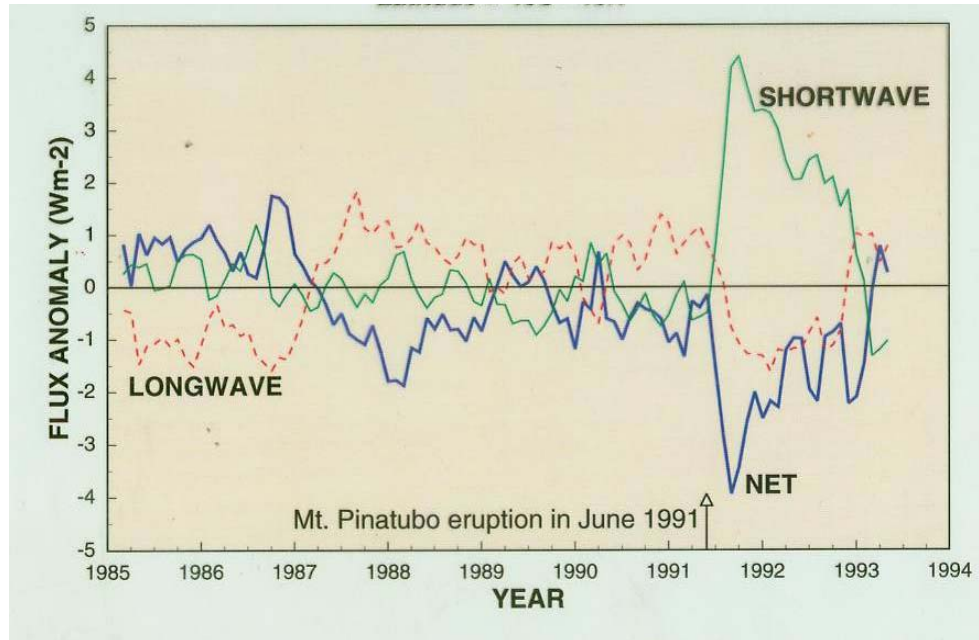


Figure 21: Changes in reflected shortwave, longwave (emitted) and net radiation from both fluxes between 40°S and 40°N for 1985 through 1989, showing effects of Mount Pinatubo eruption. (Minnis, private communication)

Interannual Variations: Our weather changes from year to year, and at present we have only limited ability to predict these changes. However, it would be extremely valuable to develop even a small capability for seasonal and yearly forecasts. One area that may pay off in this research is a better understanding of the El-Nino/La Nina oscillation. Figure 22 shows the changes of longwave radiation from average conditions at the Equator across the Pacific Ocean. The blue areas correspond to the El Nino events of 1987 and 1992. These changes of longwave radiation are due to the movement of large cloud areas in response to changing the sea surface temperature. There are many investigations to be made using the ERBE data to learn about such interannual variations.

Measurements of the Sun's Radiation: The ERBE non-scanner package included a solar monitor radiometer, which is a high accuracy instrument for measuring the radiation from the Sun. Interestingly, this solar output increases a tiny bit when there are sunspots and decreases during periods when there are few sunspots. Because the ERBE solar instruments on the Earth Radiation Budget Satellite (ERBS) have lasted over 15 years, ERBE has helped reduce the uncertainty about whether the differences between its measurements and those of other instruments were caused by the Sun or by instrument calibrations.

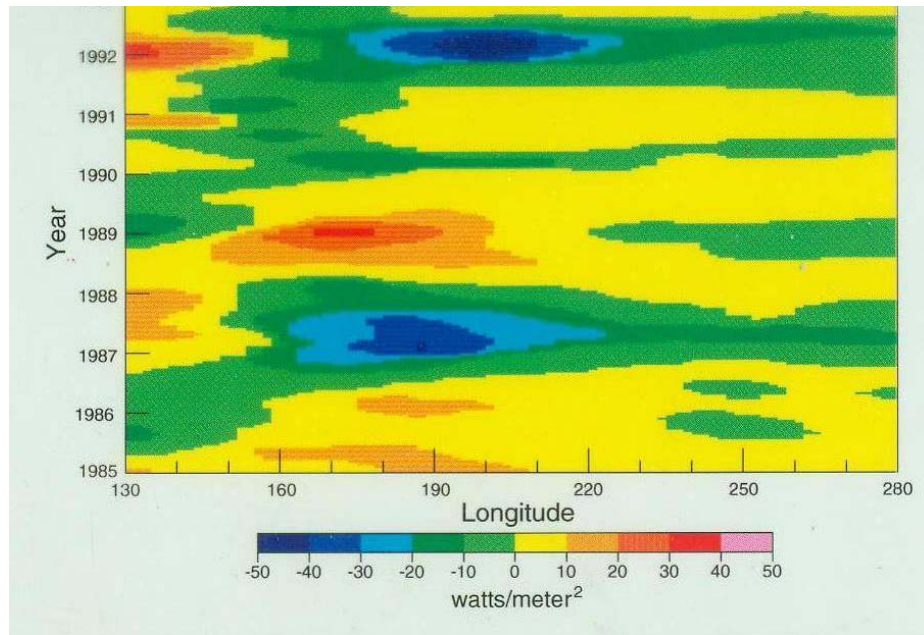


Figure 22: Longwave anomalies between 5° South and 5° North, as measured by the wide field-of-view instrument on ERBS spacecraft. (Minnis, private communication)

External Reviews

Since the 1980's, NASA LaRC has frequently had external Peer Review Panels to evaluate their atmospheric science research program. One Peer Review panel stated in 1987 that "The Radiation Sciences Branch achievements are exceptional; demonstrating its world-recognized prowess and scientific products in terms of data for the general research community and significant publications is remarkable, considering the (small) size of the branch." Another Peer Review noted that "The branch programs' impact on international science has been immense and is truly world class." A third Panel wrote: "The Panel's overall impression of the Radiation Sciences Branch's personnel is that they constitute an exceptionally harmonious group that is characterized by a high degree of interaction among scientists, both internally and externally." This teamwork was indeed an accomplishment in itself, which led to the other accomplishments.

Questions Raised by ERBE

The fact that clouds act to cool the current climate does not mean that we understand how clouds will respond if the climate changes. For example, if carbon dioxide increases trap more emitted heat, climate changes might increase the amount of high clouds and thereby enhance the greenhouse effect. Such an enhancement is called a positive feedback. The ERBE measurements did not provide enough information to identify how clouds will respond to other climate changes. To answer these questions would require long-term, accurate measurements of clouds and the Earth's radiant energy system.

Summary of ERBE Project Accomplishments:

- Archived over 5 years of scanner data from the Earth Radiation Budget Satellite (ERBS), 2 years of NOAA-9 results, and over 2 years of NOAA-10 data.
- ERBE data answered the longstanding controversy of whether clouds warm or cool the Earth. ERBE produced first data confirming clouds have a net radiative cooling effect on the planet.
- Provided the radiation standard for validating and improving General Circulation Models for climate sensitivity studies.
- Derived the first accurate diurnal variations of regional radiative parameters over the globe for climate studies.
- Determined radiative cooling as a result of the 1991 eruption of Mt. Pinatubo that was the largest ever recorded.
- Observed large longwave and shortwave radiative anomalies during the 1987 El Nino as well as the El Nino starting in 1990 that continued through 1993, which represents the longest El Nino period in the past 50 years.
- Determined solar irradiance variations and correlated results with Earth's atmospheric temperature.
- Developed a new technique for deriving narrowband albedos from temporally matched ERBE scanner and geostationary visible channel data.
- Devised and applied a new method using a combined ERBE-GOES dataset to develop and evaluate new time-space averaging techniques.
- Used combined ERBE scanner and surface flux data to show that plane-parallel models overestimate cloud albedo, models overestimate surface shortwave absorption by overestimating surface insolation, the cause is macrophysical rather than microphysical, and it is highly unlikely that observational evidence of excess shortwave absorption is due to satellite sampling errors.

The Beginning of CERES

As the decade of the 1980's came to a close, the scanning ERBE instruments aboard the NOAA-9 and -10 spacecraft had each met the requirement of operating for 2 years and stopped. The non-scanning instrument aboard the ERBS continued to perform with no problems. The ERBE Data Processing System was now generating data products from the measurements and these products were being used by researchers to learn about the relationships between radiation and climate. With the value of radiation budget data demonstrated, it was time to initiate a project that would become a successor to ERBE.

In 1987, NASA initiated the Earth Observing System Program, which would fly a number of instruments on a set of spacecraft so as to study the Earth, its atmosphere, oceans and ice. The first two of these spacecraft would be the Terra and Aqua satellites, which would be placed in Sun-synchronous orbits.

Bruce Barkstrom proposed a project that would put radiation budget instruments on these spacecraft. This project would build on the successes of ERBE and go far beyond. For this project he selected the name Clouds and the Earth's Radiant Energy System (CERES). This is name of the Roman goddess of agriculture, home, family and stability. A gilded statue of Ceres stands atop the commodities market building in Chicago. One of the early hopes of radiation budget research was to understand interannual variations of climate well enough to make seasonal forecasts that would benefit agriculture.

The CERES project would go beyond ERBE in three ways. First, the data record would be much more accurate than ERBE. When measuring Earth's radiation budget there are three sources of error in the final data products: the instrument, the retrieval of fluxes from the measurements, and the averaging over the day from the limited measurements available. CERES would attack all three of these error sources. The new project would use knowledge gained from the ERBE instrument to reduce measurement errors by a factor of two. Also the field of view would be reduced by a factor of two, thus giving more uniform fields for which bidirectional reflectance functions (BDRFs) would be used. To reduce the errors in the retrieval of fluxes from the radiance measurements, improved BDRFs are required, which in turn required more measurements from which models would be developed. The models for ERBE had been developed using 208 days of measurements from the ERB instrument aboard the Nimbus-7 spacecraft. The CERES project would have one instrument aboard a spacecraft operating in cross-track scan so as to map the geographic variation of the radiance and another instrument would rotate in azimuth and nadir angle to measure radiation in all directions so that more accurate BDRFs could be created. These improved descriptions would reduce the error of the fluxes retrieved from the measured radiances. Finally, to reduce the errors in computing the daily average radiation fluxes, a pair of instruments would fly on a morning and an afternoon spacecraft, and also data from the geostationary meteorological satellites would be brought in to define changes in radiation between the times of CERES measurements. CERES instruments were selected to fly in pairs on both the Terra and Aqua spacecraft.

CERES would also expand the objectives of measuring the radiation from the “top of the atmosphere” to include the radiation flux from the Earth’s surface and from the atmosphere. These new data products required cloud information from on-board imaging instruments and geostationary meteorological satellites, and meteorological data.

The CERES project would require bringing in and processing massive amounts of data, which was a foreboding undertaking in 1990. However, Dr. Barkstrom’s avocation was computer technology and he foresaw the evolution of computers and the capacity to transfer data so that by the time the instrument was in orbit, this work could be done with reasonable resources. Without this great evolution in computational and data transfer capability, the new objectives of extracting the surface radiation budget and the radiation absorbed and emitted by the atmosphere would be impossible. It was a daring move. In the late 1980’s and early 1990’s, Dr. Barkstrom was instrumental in formulating and promoting the development of an organization for acquiring, processing, and storing the massive amounts of data, and then disseminating the data to scientific, educational and policy-making communities. This organization is known today as the Langley Atmospheric Science Data Center (ASDC).

A proposal was prepared and submitted by Dr. Barkstrom to NASA HQ to build, calibrate and fly six CERES instruments. Concurrently, Edwin Harrison led the strategic development of a proposal to use the data for scientific investigations, with Dr. Bruce Wielicki as the Principal Investigator. The Langley Team had proven itself, the need for radiation budget data had been demonstrated and the new proposal was a major step forward. Both proposals were accepted, and CERES was funded for a new start.

An Announcement of Opportunity was released by NASA HQ and the Science Team was selected (see Table 2). Figure 23 shows the CERES Science Team members. The LaRC researchers, the Science Team and the support contractors were divided into working groups. The Instrument Group (figure 24) was led by Robert B. Lee, III, who had previously worked with the ERBE instruments and would direct the development of the CERES instruments in regard to scientific issues. Lou Smith would support the Instrument Working Group with analyses to address various questions. Also, Professor Robert Mahan of Virginia Tech received grants to develop computer models to complement this work. Kory Priestley, a doctoral student, would play a key role in this work and then join LaRC to continue his involvement in CERES. Richard Green had led the Inversion Group for ERBE and would lead this work for CERES. David Young assumed leadership of the Temporal Interpolation and Spatial Averaging (TISA) Group. Tom Charlock was selected to lead the new Surface and Atmospheric Radiation Budget (SARB) working group (figure 25). For the development of the Bidirectional Reflectance Distribution Functions (BRDFs), Norman Loeb, a recent Ph.D. from McGill University was brought in. To select the correct BRDF, it is necessary to first identify the presence of cloud and its type. Pat Minnis had built a team that would develop the cloud identification algorithms. The Science part of CERES was in place.

Table 2: CERES Science Team Members.

Researcher	Institute
Bruce R. Barkstrom, PI Instrument	LaRC
Robert D. Cess	State University of New York/Stony Brook
James A. Coakley	Oregon State University
Dominique Crommelynck	Royal Meteorological Institute of Belgium
Leonard J. Donner	NOAA/Geophysical Fluid Dynamics Lab.
Robert Kandel	Centre National de la Recherche Scientifique, France
Michael D. King	Goddard Space Flight Center
Alvin J. Miller	NOAA/National Weather Service
V. Ramanathan	Scripps Institution of Oceanography
David A. Randall	Colorado State University
Larry L. Stowe	NOAA/National Environmental Satellite, Data, and Information Service
Ronald M. Welch	University of Alabama/Huntsville
Bruce A. Wielicki, PI Interdisciplinary	LaRC

Langley Research Center Researchers in CERES

Bryan A. Baum	David P. Kratz	Kory J. Priestley
Donald R. Cahoon	Edwin F. Harrison	G. Louis Smith
Lin H. Chambers	Robert B. Lee, III	Tak-Meng Wong
Thomas P. Charlock	Norman G. Loeb	David F. Young
Richard N. Green	Patrick Minnis	



Figure 23: CERES Science Team. Back Row: Lou Smith, Bob Cess, Ed Harrison, Bruce Barkstrom, Ron Welch, Larry Stowe, Bob Kandel, Bob Lee. Front Row: Pat Minnis, Jim Coakley, Bruce Wielicki, Dave Randall, Wayne Darnell, Tom Charlock, Richard Green.

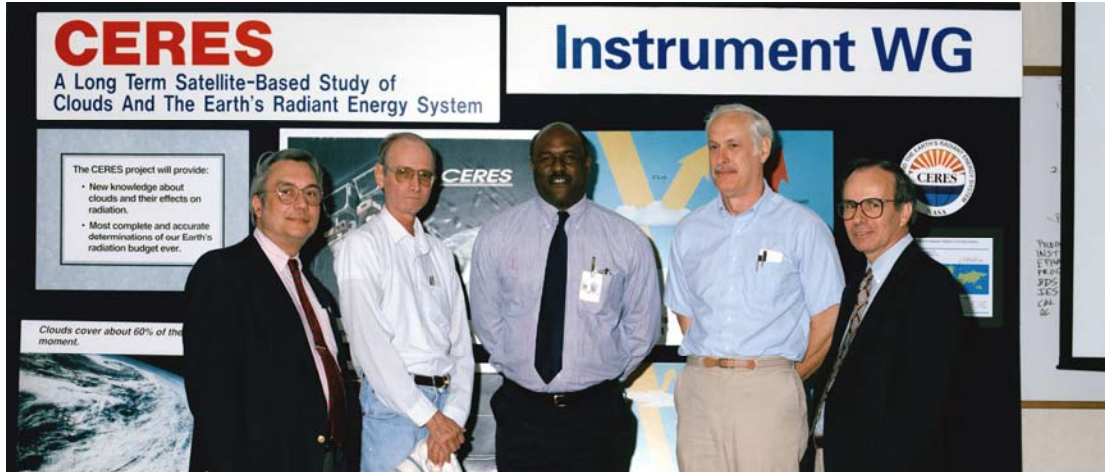


Figure 24: Instrument Working Group. From left: Bruce Barkstrom, Lee Avis, Robert Lee, Lou Smith, Jack Cooper.



Figure 25: Surface and Atmospheric Radiation Budget Working Group. Back Row: Shi-Keng Yang, John Nealy, Bob Cess, Dave Kratz, Fred Rose. Front Row: Lou Smith, Tom Charlock, Dave Randall, Anand Inamdar, Wayne Darnell, Shashi Gupta.

On the Project side of CERES, which had the responsibility of managing the design and development through build, environment testing and calibrating of the instruments and having them integrated with the spacecraft, there was also an experienced team from ERBE. Charles Woerner had become Deputy Chief of the Projects Division. Jack Cooper was selected as Project Manager for CERES. Leonard Kopia was selected to be the Instrument Manager.

A statement of work was prepared and a Request for Proposals was released by LaRC. The Space Division of TRW, in Redondo Beach, California, won the competition. A major factor in their selection was their including the Radiation Calibration Facility in their proposal. Upgrades to the thermal-vacuum tank that had been used for the ERBE instruments would be designed and built in parallel with the instrument. Steve Carman, who had been TRW's Lead Calibration Engineer for ERBE, was named as the TRW Project Manager for CERES. Tom Evert, a key systems engineer during the ERBE development, would be TRW's Chief Engineer for CERES. The contract called for six CERES instruments to be built and calibrated. These were designated the Proto-Flight Model and Flight Models 1 through 5.

CERES in Orbit

The ERBE scanning radiometer aboard the ERBS spacecraft ceased operation in 1990, after providing data for five years. There was a strong desire to fly another Earth radiation budget instrument as soon as possible. Dr. Joanne Simpson, the First Lady of Meteorology¹, was leading a team at the Goddard Space Flight Center, to develop a concept that would become the Tropical Rainfall Measuring Mission. The primary instrument for this mission was a Precipitation Radar. Other instruments would support this radar. The Proto-Flight Model of CERES was chosen to fly on this spacecraft to complement these instruments. This project was a collaborative effort between NASA and the Japanese Space Exploration Agency (JAXA). The spacecraft was built and launched by JAXA and the Precipitation Radar was built by JAXA. The remaining instruments, including the Proto-Flight Model of CERES, were supplied by NASA. Figure 26 is a drawing of the TRMM. The spacecraft was placed into a precessing orbit in November 1997. The CERES Proto Flight Model (PFM) began operating a month later. Initially, the instrument operation matched expectations. Unfortunately, an electronic component began to deteriorate and the instrument was turned off in order to preserve its remaining life for later use.

¹Joanne Simpson was the first woman in the U. S. to receive a doctorate in meteorology. She made major advancements in tropical meteorology and received numerous awards, including the Carl Gustav Rossby Award, the highest award of the American Meteorology Society.

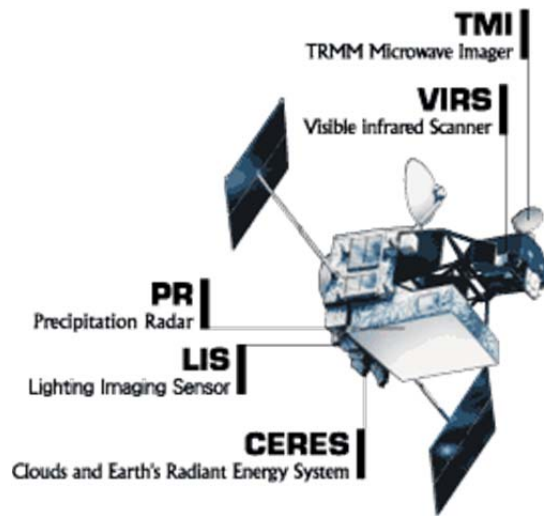


Figure 26: The Tropical Rainfall Measuring Mission spacecraft, showing CERES and the other TRMM instruments.

The Terra and Aqua spacecraft would each carry two CERES instruments. One CERES would operate in cross-track scan so as to map the geographical distribution of radiation. The other CERES would operate in a biaxial mode to make measurements from which the amount of radiation in each direction as it leaves the atmosphere can be computed. Flight Models 1 and 2 were mounted on the Terra spacecraft, which was placed into orbit in December 1999 by an Atlas 2C launch vehicle. The contamination covers were opened in February 2000 and the two instruments began taking data. Flight Models (FMs) 3 and 4 were placed on the Aqua spacecraft, which was launched in May 2002. In June 2002 these two CERES radiometers began measuring the Earth's radiation. As of 2013, there are more than 12 years of Earth radiation measurements from both CERES instruments on Terra and over 11 years of data from FM-3. Flight Model 4 lost the shortwave channel in 2008, after operating for 6 years.

By the time of the Aqua launch, several changes had been made in key personnel in CERES. Edwin Harrison retired and Bruce Barkstrom moved first to head the ASDC and later left NASA to join NOAA. Bruce Wielicki became the CERES PI. Dr. Wielicki later became involved in exploring new, advanced mission and sensor concepts for climate research and Norman Loeb succeeded him as PI. Robert Lee retired and Kory Priestley became the head of the Instrument Working Group and the science lead for the CERES instruments and their further development. The Earth radiation torch had been passed to a new generation.

CERES FM-5 on the NPP Spacecraft

After CERES instruments had been on Aqua for a few years, concern grew that the Earth Radiation Budget (ERB) Climate Data Record would be disrupted by failure of the aging CERES instruments. The scientific contributions using ERBE and CERES data were continuing and the need for the high quality measurements had become recognized by the scientific leadership in the climate community. Continuation of the ERB Climate Data Record had been identified as critical in the 2007 NRC Decadal Survey. Also, the World Climate Research Program in its report “The Global Climate Observing System” reiterated the need for ongoing Earth radiation budget data. NASA and NOAA agreed to fly the final existing CERES FM-5 on the National Polar-Orbiting Partnership NPP spacecraft to continue the critical Climate Data Record begun by the ERBE instruments in the mid 1980’s and continued by the CERES instruments on the Terra and Aqua spacecraft. The NPP spacecraft was placed in orbit 28 October 2011. Figure 27 shows the NPP spacecraft, with CERES FM-5. Once it was placed successfully in orbit and shown to operate well, this spacecraft was renamed the Suomi-NPP in honor of the Father of Satellite Meteorology.

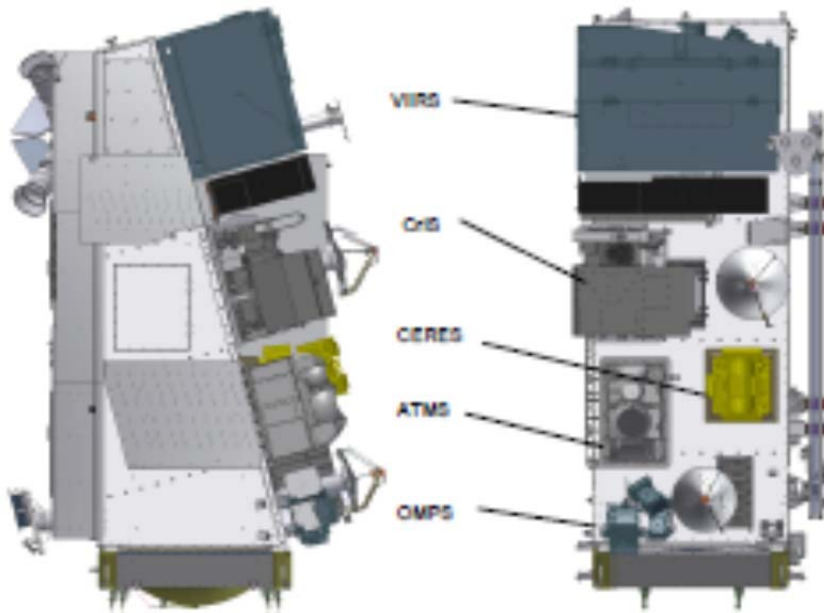


Figure 27: Layout of Suomi NPP Spacecraft, showing CERES and other instruments.

CERES Accomplishments

The CERES instruments aboard the Terra and Aqua spacecraft have produced high quality data for over a decade. These data can be used for many investigations, e.g., year-to-year changes in climate. A number of data products are available to the science community.

Improvement of Measurement Accuracies: One objective of CERES was to improve the radiometer to reduce measurement errors. Robert Lee and the TRW (now Northrop Grumman) engineering team used their experience with ERBE to improve the instrument design, including the on-board calibration devices, and the ground calibration of the instruments. Bob Lee and Kory Priestley used the accumulated knowledge to create better ways to calibrate the instruments on the ground and then in space in order to generate accurate radiances.

Improvement of Radiation Directional Models: Another objective of CERES was to improve the accuracy of the fluxes by creating better bidirectional reflectance distribution functions (BRDFs) with which to compute fluxes from radiance measurements. This caused a dilemma, as several years of data would be needed to develop the new BRDFs before the fluxes could be computed more accurately. The solution to this problem was to use the earlier BRDFs to compute fluxes until the new BRDFs became available. Another edition of fluxes was then computed with the improved models. After enough measurements were available, Norman Loeb led the development of these models. CERES made more measurements for this purpose than had ever been made before, radiation transfer codes had an additional two decades of development, and computers to perform the needed calculations were immensely more powerful than for the ERBE generation of models. Previously, there had only been enough biaxial scanning measurements to develop BRDFs for 12 scene types, with coarse angular resolution. The new CERES BRDFs were defined for 200 scene types with much smaller angular intervals. Loeb's new BRDFs greatly reduced the errors in fluxes. Figure 28 shows one view of the CERES BRDFs for overcast ice cloud.

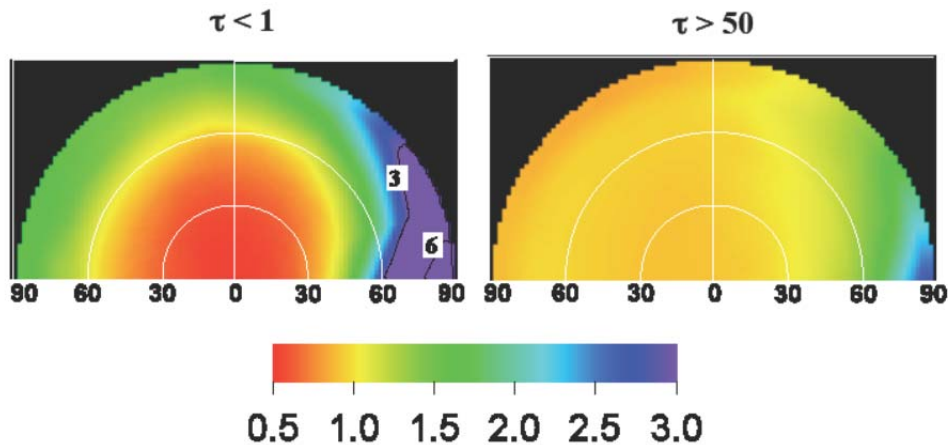


Figure 28: CERES Bidirectional Reflectance Distribution Function for overcast ice cloud, for Sun between 60° to 70° from overhead. (N. Loeb, private communication)

Surface and Atmospheric Radiation Budget: The new objective of CERES, to create a data product for the surface and atmospheric radiation budgets, was quite ambitious. To compute the fluxes of radiation at various levels within the atmosphere requires an immense amount of data to describe the atmosphere over the globe and then an incredible amount of computation involving radiative transfer codes to calculate the fluxes. Tom Charlock led the SARB Working Group to develop techniques and software for accomplishing these tasks. Fred Rose and Seiji Kato worked with Qiang Fu (University of Utah) to modify the Fu-Liou radiative transfer code for SARB application. To bridge the gap of MODIS aerosol optical depth retrieval and provide information on aerosol composition, an aerosol transport model developed at NCAR (MATCH) was also included in the routine SARB data processing. To facilitate validations of the surface fluxes from SARB with surface radiometer measurements, David Rutan developed a website (<http://www-cave.larc.nasa.gov/cave/>) that included all surface sites that are equipped with well-calibrated radiometers and greatly simplified the previously time-consuming validation task.

In addition, Tom Charlock, Greg Schuster, Bill Smith, Jr., Ken Rutledge, and Jerry Purgold established and operated a radiation monitoring station on the Chesapeake Lighthouse Platform in the Atlantic Ocean 25 km off the Virginia coast. Although there are many radiation monitoring stations on land, this oceanic station was unique and gave information for validating SARB results over ocean. At this ocean platform, a unique spectral photometer was mounted on a tracker to scan the ocean surface. Wenying Su utilized these data to verify the half-century old Cox and Munk model for directional distribution of sunlight reflected from the ocean surface.

The next several figures show some data products that were generated by SARB. Figure 29 is a global map of longwave radiation downward at the surface, or how much heat is radiated to the surface by the atmosphere. Figure 30 shows the longwave radiation flux away from the surface. Figure 31 shows the net shortwave radiation flux at the surface. The atmospheric divergence of longwave radiation between 500 mb and the surface is shown in figure 32. (The blue indicates that the atmosphere radiates downward to the surface, and the convention is that downward flux is negative.) Such information opens new areas of research into how radiation drives climate. Wenying Su compared the vertical flux profiles from SARB with those produced by the Hadley Center model and identified the deficiencies of cloud schemes at different heights.

The SARB data processing enabled the generation of other useful radiation products. Wenying Su led efforts to produce ultraviolet (UV) radiation and Photosynthetically Active Radiation (PAR). UV radiation is divided into three bands (UVA, UVB, and UVC). UVB is associated with vitamin D production in the human body, but excessive exposure to UVB can also cause skin cancer. PAR is important to agriculture and forestry. Figure 33 shows the diffuse component of PAR over the contiguous United States. Maps of UV radiation (total, UVA, and UVB) are shown in figures 34, 35 and 36.

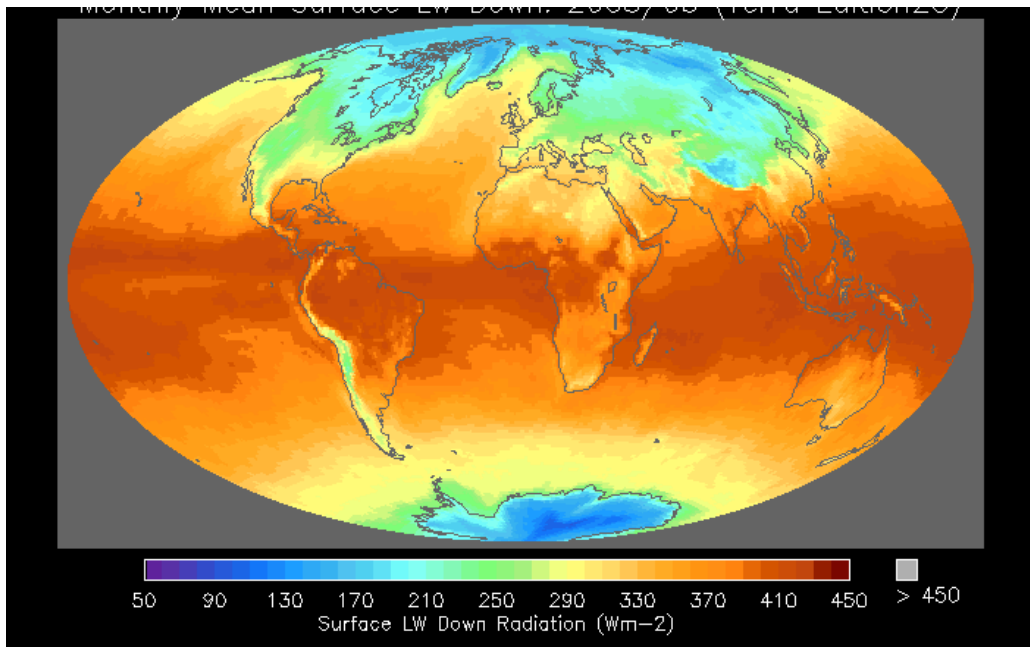


Figure 29: Monthly-mean map of downward longwave radiation from the atmosphere to the surface for March 2005.

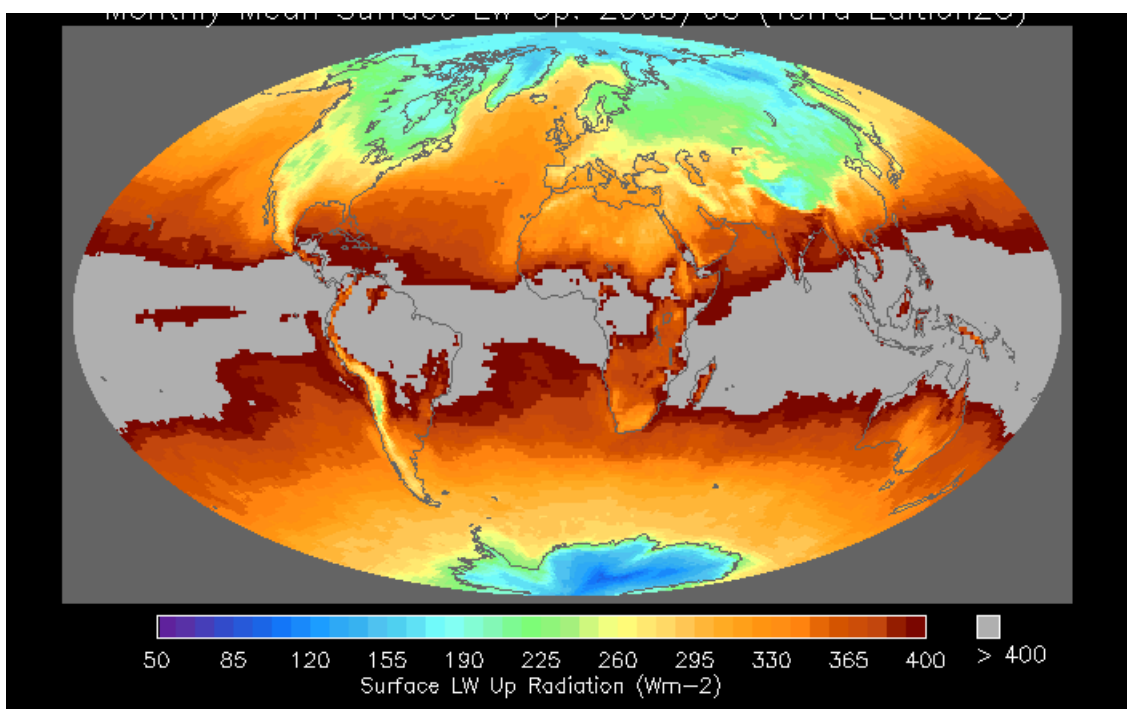


Figure 30: Monthly-mean map of upward longwave radiation from the surface for March 2005.

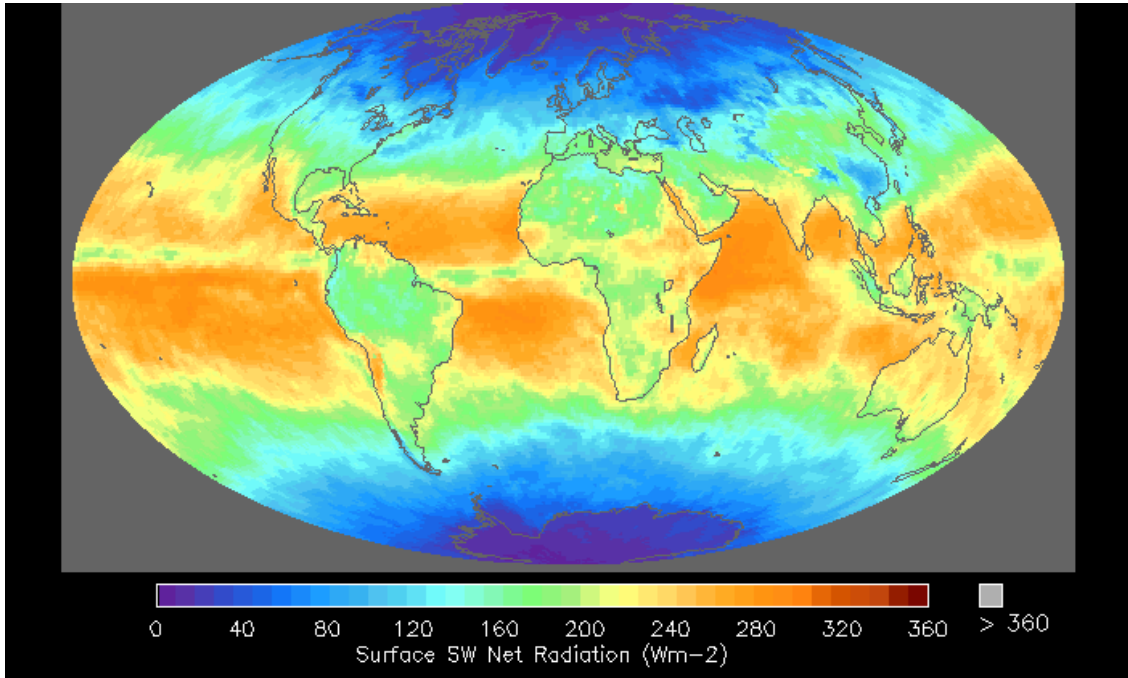


Figure 31: Monthly-mean map of net shortwave radiation at surface for March 2005.

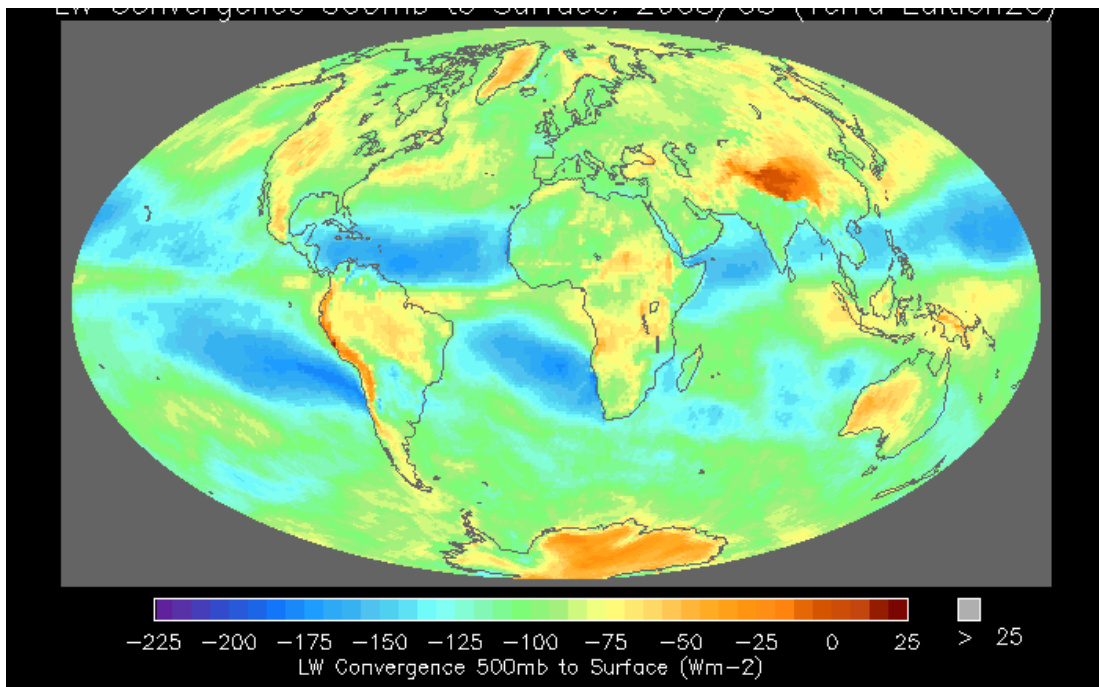


Figure 32: Atmospheric Radiation Divergence Longwave component, 500mb to surface for March 2005.

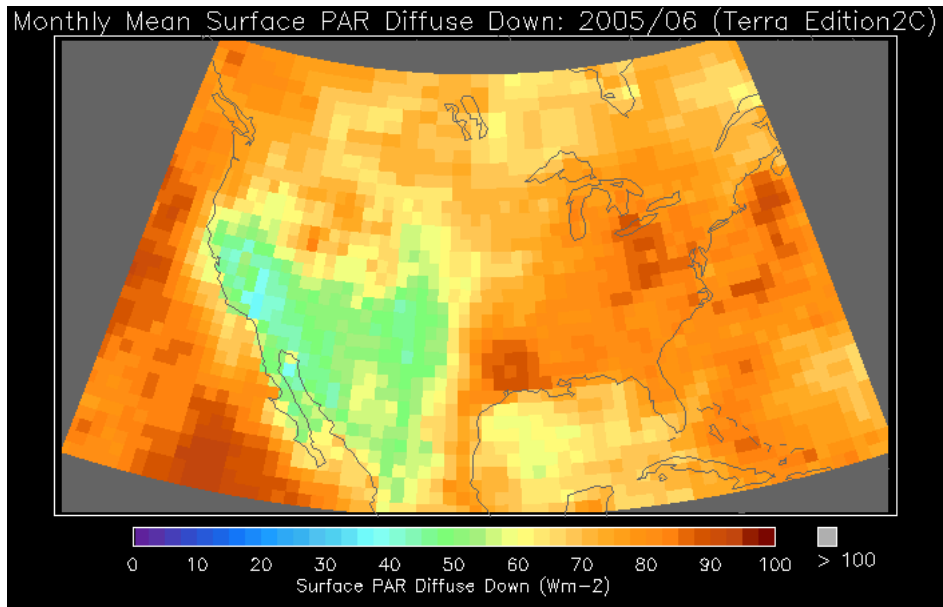


Figure 33: Photosynthetically Active Radiation over contiguous US Diffuse Component, June 2005.

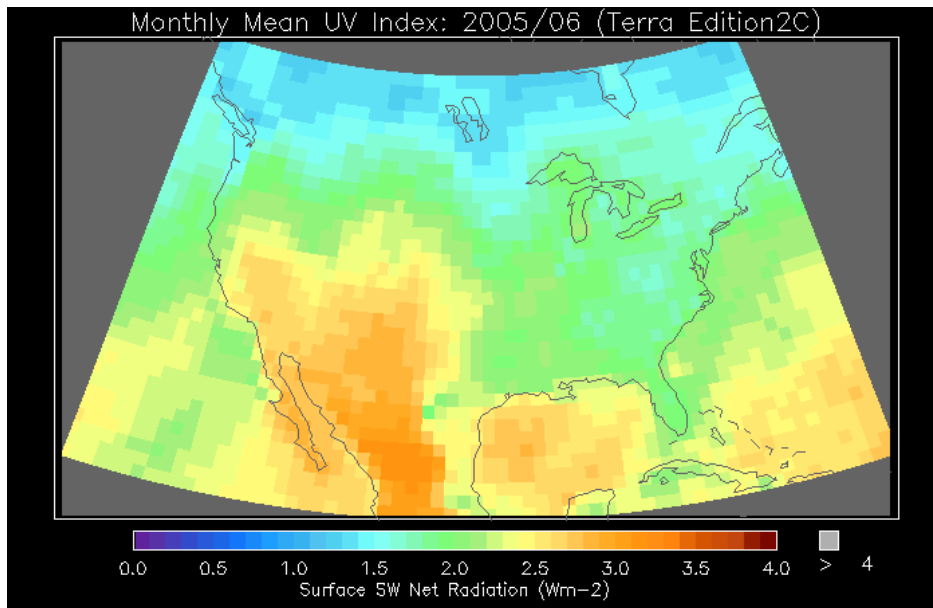


Figure 34: Monthly-Mean UV over contiguous United States, June 2005

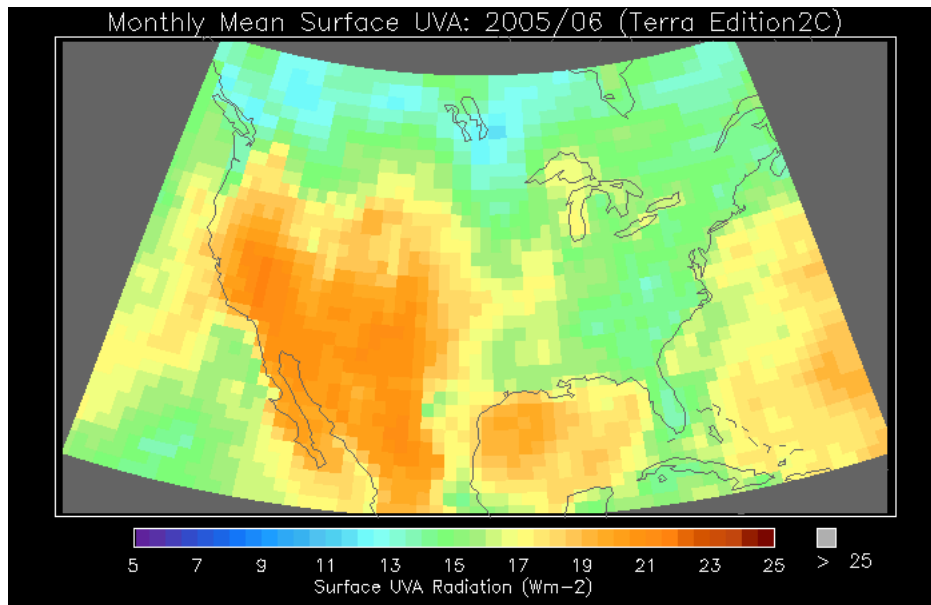


Figure 35: Monthly-Mean UVA over contiguous United States, June 2005.

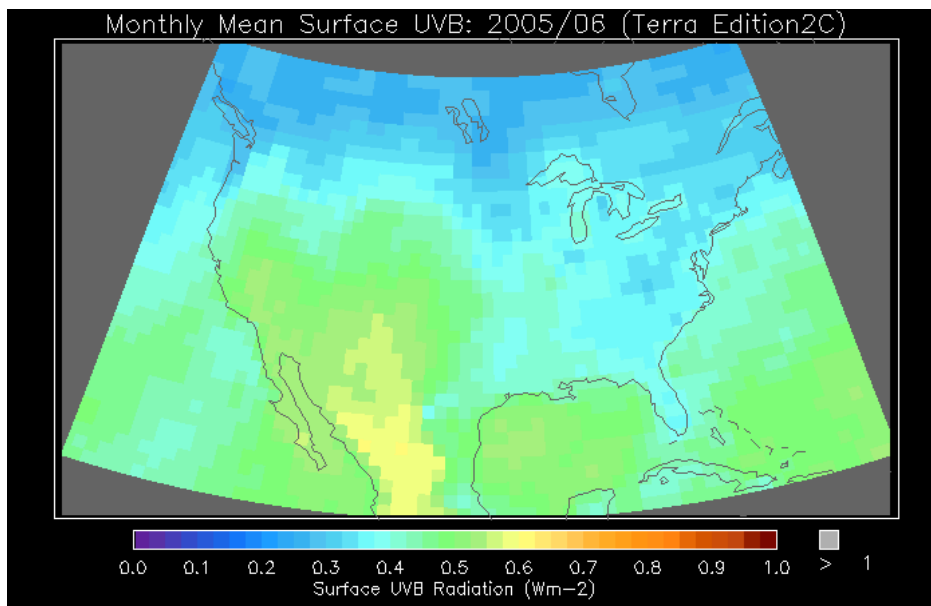


Figure 36: Monthly-Mean UVB over coterminous United States, June 2005.

Scientific Achievements of CERES as of 2012

- CERES observations (Kato et al., 2006) were used to show that rapid decreases in Arctic sea ice cover are accompanied by large increases in Moderate Resolution Imaging Spectroradiometer (MODIS) cloud cover and negligible changes in CERES shortwave (SW) TOA fluxes. These results suggest that changes in Arctic sea ice are compensated by changes in cloud cover. Consequently, any ice-albedo feedback could be dampened because of increased cloud cover.
- CERES data were used to isolate the effect of large scale dynamics on the observed radiation budget and cloud properties in the tropics. Observed tropical mean changes can be as large as $\pm 3 \text{ Wm}^{-2}$, while the dynamical components are generally smaller than $\pm 0.5 \text{ Wm}^{-2}$.
- Trenberth and Fasullo (2009) used CERES Terra, ocean heat content, and reanalysis data to provide a summary of the overall energy balance for the global atmosphere, ocean and land domains. Of the 2.6 PW of net radiation into the system over ocean, approximately 0.4 PW are absorbed by the ocean, and 2.2 PW are transported from ocean to land by the atmosphere to compensate for the net radiation out of the system over land. Approximately 0.01 PW of the net flux imbalance goes into land and melting of ice.
- The Intergovernmental Panel on Climate Change (IPCC; 2007) fourth assessment report recognized that measuring the radiation balance accurately is fundamental in quantifying the radiative forcing of the system as well as diagnosing the radiative properties of the atmosphere and surface, which are crucial for understanding radiative feedback processes. The report identified ERBS/CERES global net TOA radiation data as providing evidence for decadal changes in TOA radiative fluxes over the last two decades and that the changes in the planetary and tropical TOA radiative fluxes are consistent with independent global ocean heat-storage data.
- CERES and other observations of the components of the water and energy cycles are used together with climate models to examine evidence for robust responses and links between the tropical energy and water cycles over the period 1979–2006.
- CERES observations are used together with reanalysis data to determine new estimates of large-scale Arctic atmospheric energy budget. Monthly mean anomalies of budget terms are used to examine conditions leading to the extreme seasonal sea ice extent minimum of September 2005 and the role of the ice albedo feedback process.

Surface Radiation Budget

Once LaRC had gotten the new start for the Earth Radiation Budget Experiment and the Radiation Sciences Branch had been formed, the organization was committed to work in the area of radiation budget. As the work on ERBE became organized, the question was raised by Wally Staylor, a member of the Radiation Sciences Branch, and others: Isn't the radiation budget at the surface at least as important as it is at the top of the atmosphere? After all, we live at the surface.

The importance of surface radiation budget is shown by the Earth's energy budget diagram below (figure 37). This diagram by Trenberth et al., 2009 is an updated version of a similar figure in "Understanding Climate Change" (National Academy of Sciences, 1975). The diagram shows that parts of TOA incoming solar radiation (called insolation) are reflected back to space by clouds, the atmosphere, and the Earth's surface, all contributing to the reflected shortwave (SW) radiation (RSR) at the TOA. Some part of TOA insolation is absorbed by the atmosphere and clouds but close to half of it is absorbed at and warms the surface. The warm surface emits longwave (LW) radiation that is partly absorbed by greenhouse gases and clouds in the atmosphere, which in turn, radiate some of it in all directions. Some of the LW radiation emitted by the surface, and by the atmosphere and clouds constitutes the outgoing longwave radiation (OLR) at the TOA and escapes to space. RSR and OLR together constitute the radiation budget at the TOA. Surface loses a substantial portion of the absorbed SW energy through evaporation that, in turn, drives the hydrological cycle.

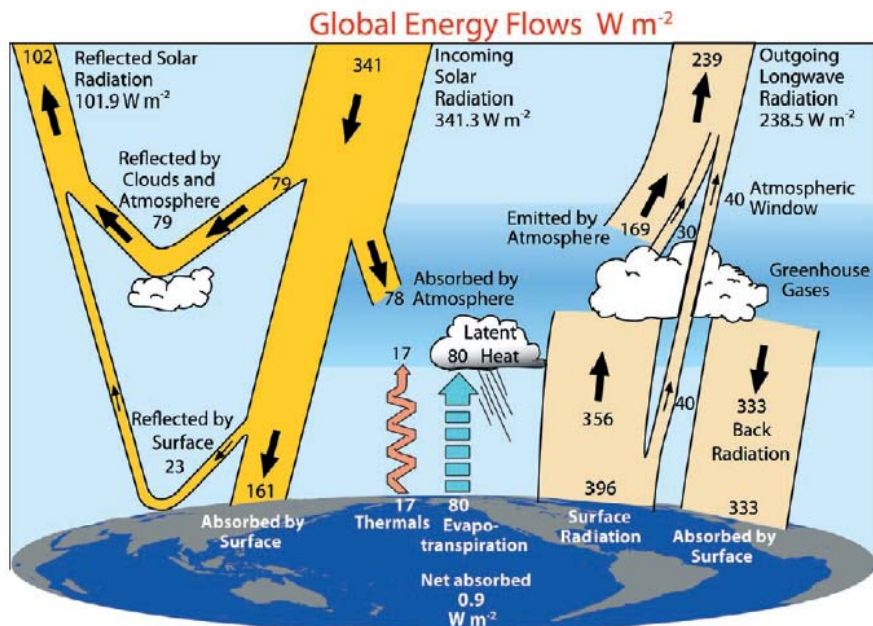


Figure 37: The global annual mean Earth's energy budget for the March 2000 to May 2004 period ($W m^{-2}$). The broad arrows indicate the schematic flow of energy in proportion to their importance. (Trenberth et al., *Bull. Amer. Met. Soc.*, vol. 90, 2009)

In order to begin a project to work on Surface Radiation Budget, it was necessary to explain what is the scientific purpose, to what resolution in time and space, with what accuracy, what is the plan for accomplishing it, and what resources are required to accomplish it. In the mid-1980s, Tim Suttles collaborated with George Ohring of NOAA to write a white paper explaining the scientific and practical importance of surface radiation, listing investigations that could be made with a Surface Radiation Budget data set and outlining a project to develop such a data base. The timing was great. The World Climate Research Program (WCRP) was being organized. ERBE would provide the energy at the top of the atmosphere and as such would be an important part of the program. The SRB program, giving radiation at the surface, would be another key part of WCRP. Dr. Robert Schiffer, Program Manager for Radiation Sciences in NASA Headquarters, was working with Dr. William Rossow of Goddard Institute of Space Studies to establish the International Satellite Cloud Climatology Project (ISCCP) as a part of WCRP. The surface radiation is highly dependent on clouds, and ISCCP would provide the required information for computing the SRB. The proposed project to develop a Surface Radiation Budget Data Base was approved and began. In 1989, the Global Energy and Water-cycle Experiment (GEWEX) project was established under the WCRP. ISCCP, SRB and a global precipitation project were initial foci for the global satellite derived data sets.

These downward and upward components of SW and LW radiation described above constitute the surface radiation budget and each of these components needed to be derived with sufficient accuracy on a global scale. At the time, downward SW and LW components were mostly derived on local scales with bulk formulas that used local measurements of meteorological parameters such as temperature, humidity, and cloud cover. Upward LW fluxes were derived from local measurements of surface temperature. Upward SW fluxes were either measured directly or derived using surface albedo (when available). These methods were certainly not useful for deriving SRB on a global scale.

Techniques would have to be developed to perform the calculations for all of these components. Radiative transfer models and detailed knowledge of atmospheric state variables (temperature, humidity, constituent concentrations, etc.) on a global scale are required to derive surface radiation parameters. Even though some radiative transfer models for deriving SRB components were available at the time, most of them were computationally intensive and inappropriate for use on a global scale. Computationally fast models would have to be developed and used with global scale meteorological inputs that became available recently from sounding instruments on board the TIROS-N satellites.

In 1981, Shashi Gupta joined Ed Harrison's branch as a NASA/NRC postdoctoral research associate. Gupta had considerable experience in longwave radiative transfer and was assigned the task of developing LW radiative transfer models for the SRB project. By early 1983, he had developed a narrowband longwave model and published it in the *Journal of Quantitative Spectroscopy and Radiative Transfer*. This model used local

meteorological profiles to derive surface LW fluxes that compared well with what limited surface observations were available at the time. Experience with this model showed that, with computer resources available at the time, this model did not run fast enough to accomplish global scale processing on a long-term basis. Realizing this, Gupta immediately started on the development of a parameterized model based on the results obtained from the narrowband model. To ensure global applicability of the resulting parameterization Gupta used globally sampled satellite sounder profiles from the TIROS Operational Vertical Sounder (TOVS) and globally gathered radiosonde data as inputs. At the same time, working alongside Wayne Darnell and Wally Staylor of the Radiation Sciences Branch, his work resulted in two publications in the *Journal of Climate and Applied Meteorology* (1983 and 1986) validating the results of the narrowband model. The parameterized model was published in the *Journal of Climate* in 1989 with refinements to follow in the *Journal of Applied Meteorology*, 1992.

At LaRC, Wally Staylor created an algorithm for computing the solar radiation at the surface, or downward shortwave flux, which took into account the effects of the atmosphere including clouds without having the detailed information required by the more sophisticated codes. This method worked for practically all cases and gave results which were as good as those from the complex codes, given the information available about the atmosphere. The upward shortwave flux could be computed from the downward shortwave flux if one knew the reflectivity, or albedo, of the surface. Maps of the albedo of the surface were developed for this purpose. A brief description of Staylor's methodology and initial results were published in the *Journal of Climate* (1988). Wally retired in 1994 without publishing his model or its origin. There was no clear derivation of the method from "first principles," that is, one could not begin with known equations and get the equations that Staylor created. Consequently, the model was not accepted by the science community. That situation was substantially resolved in 2001 when Shashi Gupta, Dave Kratz, Paul Stackhouse, and Anne Wilber prepared a NASA Technical Publication establishing the scientific basis of the Staylor model. This model is continually updated and still used for quality assurance for SRB shortwave data products and was incorporated into the CERES (Clouds and the Earth's Radiant Energy System) project to compute a fast estimate of fluxes.

The parameterized SW model developed by Staylor and Gupta's LW parameterization were used to produce SRB parameters, initially on a 10° equal-area grid and then on a 5° equal-area grid using TOVS meteorological inputs from NOAA-6 and NOAA-7 satellites. The spatial resolution a TOVS measurement was about 300 km, so producing SRB data at higher spatial resolution was not considered scientifically sound. Anne Wilber and Nancy Ritchie provided programming and analysis support for developing the algorithms and creating the database.

Once 3-hourly ISCCP-C1 data on a 2.5° equal-area grid became available starting in 1988, the team restructured the code and produced SRB data on the ISCCP grid. Darnell et al. published surface SW and LW fluxes from these algorithms and ISCCP-C1 inputs for mid-seasonal months of 1983-1984 in the *Journal of Geophysical Research* (1992).

Figures 38 and 39 show examples of these results. Figure 38 shows the net shortwave flux (the Sun's radiation flux minus the reflected flux), or total sunlight absorbed at the surface, for July 1983. Over most of the Earth between 30°N and 30°S the absorbed flux is between 200 and 300 watts per square meter. In the mid-Atlantic Ocean, there is an area where the flux is over 300 watts per square meter. This is the location of the Azores High or Bermuda High, where there is little cloud cover. The clouds over India for the monsoon reduce the sunlight at the surface. South of 30°S, in Southern Hemisphere winter, the net shortwave flux decreases rapidly. Within the Antarctic Circle, it is polar night and the sunlight is zero. Figure 39 shows the net longwave flux, i.e. the radiation emitted by the surface minus the downward radiation from the atmosphere. The deserts of North Africa, the Middle East and the Southwest of the U. S. radiate a net of over 100 watts per square meter. Antarctica gives off 75 watts per square meter. This large amount is because there is little cloud cover and the air has very little humidity, so that the air radiates very little back to the surface. Over the oceans south of 30°S, the water is much warmer and radiates more than the ice of Antarctica, but there is much cloud and the air has much water vapor, so that the atmosphere radiates much radiation to the surface. . This was soon followed by the publication of cloud radiative effects on surface fluxes by Gupta et al. in *J. Geophysical Research* (1993) and sample SW and LW results from that work for July 1985 are shown on figures 40 and 41 respectively.

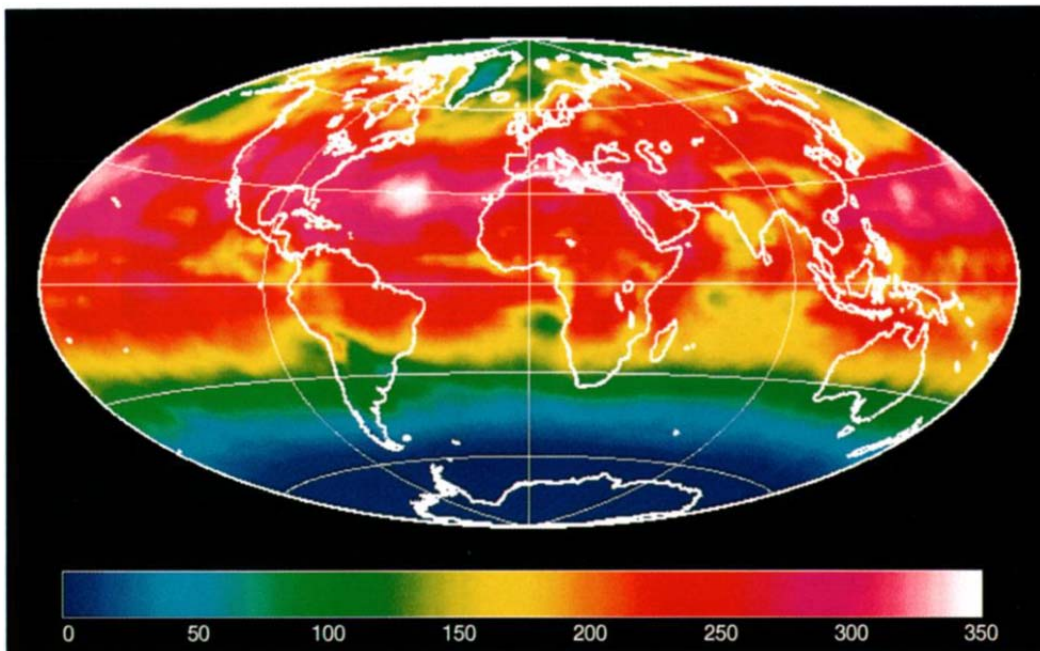


Figure 38: Distribution of net shortwave flux at surface for July 1983 (Watts per square meter).

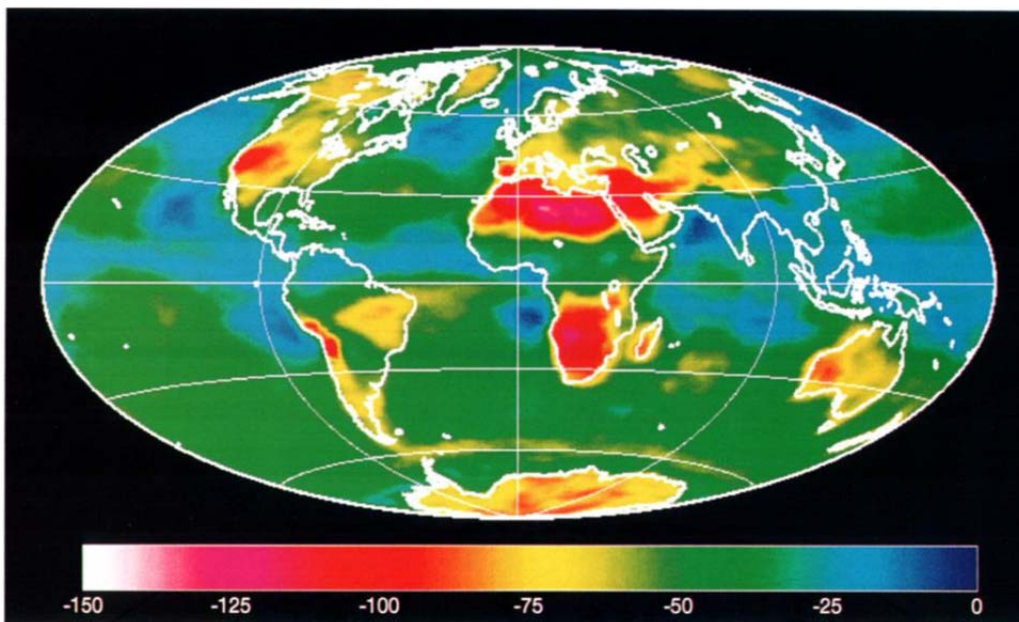


Figure 39: Distribution of net longwave flux at surface for July 1983 (Watts per square meter).

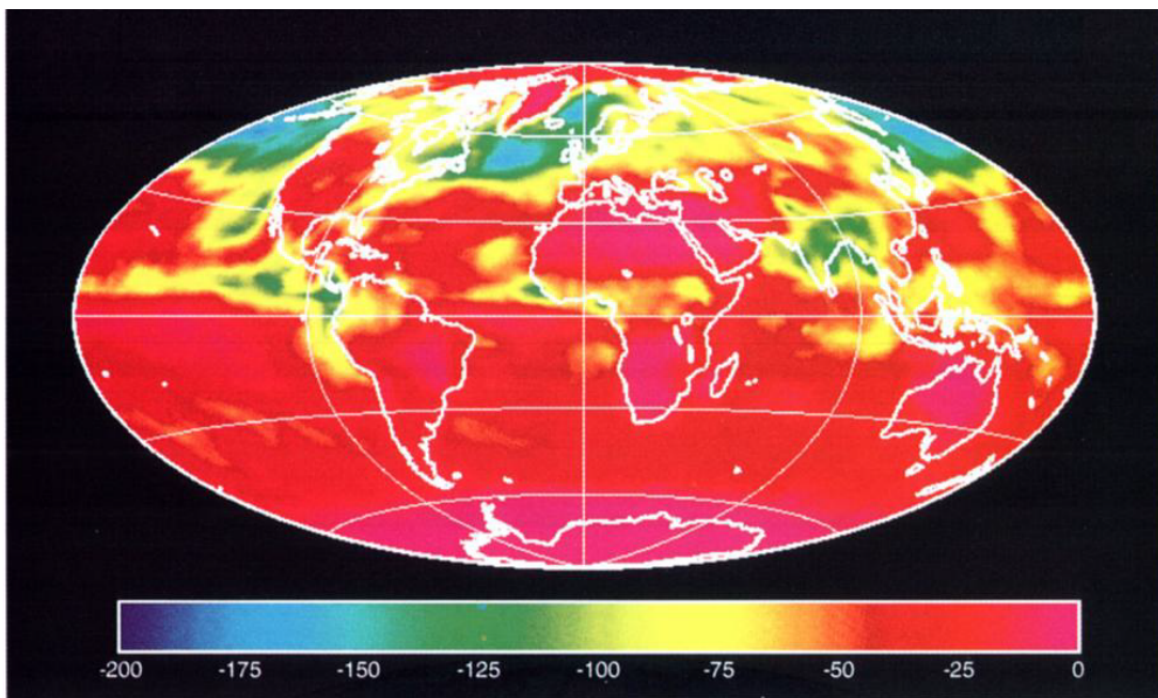


Figure 40: Distribution of shortwave cloud forcing at surface for July 1985 (Watts per square meter).

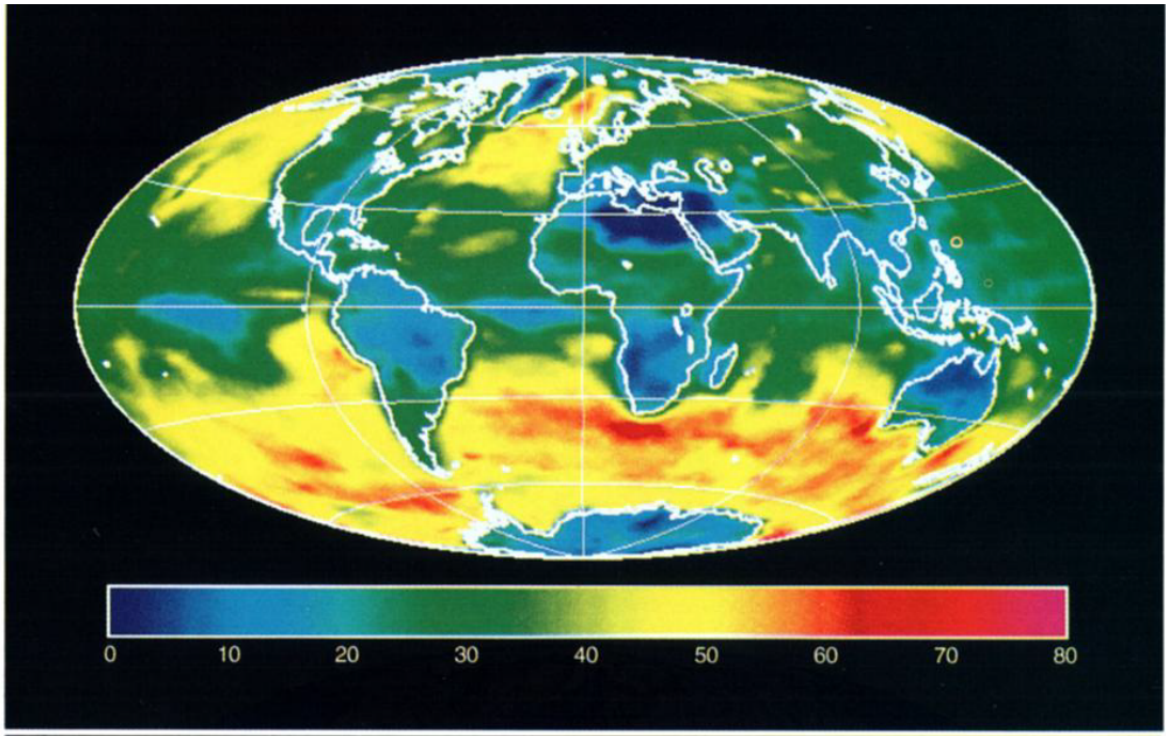


Figure 41: Distribution of LW cloud radiative effect at the surface for July 1985 (Watts per square meter).

In the meantime, several national and international programs were started for measuring both SW and LW fluxes from ground-based radiometers with the express purpose of validating satellite retrievals of surface fluxes. A program for measurements of surface radiation was set up at LaRC under the leadership of Dr. Charles Whitlock. Charlie set up field experiments to measure radiation components at the surface at forested locations. These experiments would provide data to validate the algorithms being developed and also give the team experience with the kinds of data they would be receiving from, soon to be available, measurements from around the world. Charlie enlisted Gerald Purgold as the experiment technician. Purgold had the necessary expertise in hardware and electronics and that made the measurement program successful. The LaRC group made full use of available surface measurements to validate their products and the effort was documented in the above-mentioned publications. Based on experience and confidence gained from validation of their products, the LaRC group processed the entire record of ISCCP-C1 data that covered an eight-year period (July 1983 to June 1991). This data set was announced and made available to the worldwide science community through a brief report in the GEWEX News, a newsletter published by the International GEWEX Project Office (IGPO). Validation of the eight-year data set and a climatology of SRB products based those data were published in the Journal of Climate (1999).

Wayne Darnell retired in 1995, and the modeling program was consolidated with the measurement program under Whitlock's leadership. Whitlock retired in 1996 and Paul Stackhouse, who had just earned his Ph.D. in atmospheric sciences from Colorado State University, joined the LaRC CERES team. He led the development of a radiative transfer based longwave algorithm that was subsequently approved by GEWEX to become the official GEWEX LW flux algorithm. Stackhouse was subsequently selected to lead the SRB Program in 1997.

Stackhouse steered the program toward deriving SRB at a resolution of 1 degree. To achieve that objective, he started with ISCCP data for individual measurements and derived required cloud properties on a 1-degree resolution. The Pinker and Laszlo (1992) radiative transfer model for SW and the Fu et al. (1997) model for LW provided greater detail and were brought in as primary processing algorithms. Staylor's parameterized algorithm for SW and Gupta's algorithm for LW were retained for the purpose of quality assurance. A reanalysis data product from the Global Modeling and Assimilation Office (GMAO) at NASA GSFC, designated as GEOS-1, was chosen to provide meteorological inputs for the models. (Reanalysis data sets are generated to provide the best possible description of the atmosphere and surface for researchers.) The SRB team now included Paul Stackhouse, Shashi Gupta, Stephen Cox, and Colleen Mikovitz to share the increased modeling, data handling, and product validation responsibilities as Nancy Ritchie left and Anne Wilber was reassigned.

The NASA/GEWEX SRB products have continued to improve over the last two decades because of the improvements to the algorithms based on insights gained from continuing validation. Newer versions of ISCCP and GEOS data sets also contributed to product improvements and to the length of the data record because of the increasing coverage period. A 12-year data set was made public in 2004, followed by the 22-year Release in 2006, and 24.5-year Release in 2011. Each release was announced in the GEWEX News.

In addition to the importance of SRB data for scientific investigations, these data have many other applications: solar power, building design, agriculture, etc. In order for these data to be used, it was necessary to connect with the industries that had uses for the data. Often this meant discussions to find how the data would be used and in what form it was needed for various applications. Also, to connect with them required letting the industries know that the data were available and how to get it. A Bridge Builder is required to bridge the chasm between the scientists who produce these data sets and the people who use them in practical applications. Roberta DiPasquale was given this task. She attended conferences and meetings outside the usual science arena in order to meet the practical users and their needs. The SRB team then generated data products in the form that these users needed. The Surface meteorology and Solar Energy (SSE) web site created in 1997 made it possible to provide information to the renewable energy industry. Users of this site include the U. S. Air Force, U. S. Department of State, U. S. Department of Energy, USDA Forest Service, USGS Headquarters, NOAA, the World Bank, UNESCO, American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), BP Solar, Shell Renewables and Duke Solar Energy. The

experience with the SRB data users outside the scientific community demonstrated clearly that it is not sufficient for scientists to put their data in an archive, even though it is accessible by the web. A Bridge Builder is needed to make the necessary connections with a broader community of users.

One early application of SRB data was for design of solar cookers and solar powered refrigerators for refugee camps in the Sahel. Accurate estimates of solar energy available at the surface were essential for determining collector areas required for running a solar cooker and/or a refrigerator. A noteworthy method of using the SRB data set is the Renewable Energy Technology Screen (RETScreen) International Project, which was developed by Natural Resources Canada. RETScreen is a tool that allows engineers, technicians and architects to design energy-efficient buildings. It has more than 230 users in over 220 countries. The Surface Radiation Budget Data Archive has been used by numerous researchers for studying climate. It is also a trove of information for practical applications, for designers of solar power plants, buildings, etc. There are many uses that could not be imagined at the beginning of the project.

Future Planned Earth Radiation Budget Research

Enough spare parts were produced or purchased to build another copy of CERES, the FM-6. This instrument will be launched on the first NOAA/NASA Joint Polar Satellite System (JPSS-1). For future missions, proposals to develop and build the next-generation instrument called Radiation Budget Instrument (RBI) are now being evaluated. The present CERES was designed in the early 1990s with 1980s technology and many of the key components are no longer available or feasible to produce. Thus, building another exact copy of the current CERES instrument was not a viable option.

The understanding of the Earth's radiation budget and capability to develop highly accurate radiometers for use in orbit has led to the Climate Absolute Radiance and Refractivity Observatory (CLARREO) Project. The Langley-led CLARREO mission will provide the first observations of the full spectrum of energy reflected and emitted from the Earth: the same spectrum that drives climate change forcing, response, and climate sensitivity. CLARREO will provide the first spectral fingerprints of climate change and can avoid the uncertainty of instantaneous retrievals from satellites. Furthermore, CLARREO will provide the first space-based laboratory to measure the Earth while continually verifying the measurements against international standards, a process that will improve the accuracy of the whole climate measurement system. In doing so, CLARREO will produce a benchmark of the Earth's climate, providing a standard that can be confidently compared with measurements of climate change 5, 10, 20, even 50 years after the mission's launch. Bruce Wielicki serves as CLARREO Mission Scientist. David Young served as the mission's first Project Scientist; Rosemary Baize transitioned to that role after Young accepted a Center leadership position. The CLARREO mission team includes leading climate modelers and observation scientists from different universities and agencies. A key contributor from Langley is Marty

Mlynczak who leads efforts to develop a new instrument to measure the far infrared part of the spectrum. The CLARREO team successfully completed a Mission Concept Review in fall 2010 and is currently in an extended planning phase to explore alternative, lower cost implementation strategies and reduce technical risk. The expected launch date is no earlier than 2023. An overview of the CLARREO mission is given in an October 2013 article in the Bulletin of the American Meteorological Society by Wielicki et al.

Peer Reviews of Langley Radiation Research

The research conducted in the Science Directorate is periodically reviewed by scientists from outside Langley, who have distinguished themselves by their contributions. From the beginning these reviews have rated the work of the branch very highly. One reviewer said the branch is “like swans: graceful, yet paddling furiously underneath.”

In the 2007 External Peer Review Report, it is stated that “The panel was universally impressed with the high quality and relevance of the science being performed. The program has demonstrated unprecedented leadership in space-borne earth radiation budget studies which are having major impacts upon scientific research outside of NASA.” “The CERES work is first rate and first class. The care and precision associated with calibration of the instrument and maintaining the data record are to be commended. Dr. Bruce Wielicki and the rest of the CERES investigators have clearly thought through the issue of providing outstanding and usable extended period climate records. The fusion of the data from other instruments, combined with models, to produce outstanding measurements of radiative fluxes serves as a benchmark for the community.”

Reflections on Radiation Budget At Langley Research Center

Earth radiation budget work at Langley Research Center began with the recognition of need for measurements leading to scientific data products and the areas that required work. A Team was formed to address these areas. Starting with a proposal for a passive spacecraft, they also pursued other concepts through grants. The Team polled several climate scientists to learn their requirements: what did they need, at what time and space resolution and accuracy. These questions were finally answered by a panel of the National Academy of Science. The result was that the original concept was discarded and one of the approaches studied under a grant was adopted. Success was won by perseverance and flexibility of the Team. The Team consisted of engineers with backgrounds in basic physics and mathematics and a willingness to learn. This last trait is required in a research environment, where one is always moving beyond the known into the unknown. The team approach has been continued through ERBE and CERES.

The projects were accomplished by a team of in-house scientists and contractor support staff working closely to design and build the best instruments within their abilities. Observers have often commented on the openness and close collaboration between the civil servants and their contractor colleagues.

The Science Teams that were formed from researchers from various government laboratories and universities gave an excellent return on the investments in these projects. In addition to studies that had been outlined at the beginning, important investigations were accomplished that had never been anticipated.

Annotated Bibliography

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