

Clouds and Earth radiant energy system: an overview

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Abstract

The Clouds and Earth radiant energy system (CERES) instrument was first flown aboard the TRMM spacecraft whose 35° inclination orbit allowed for the collection of radiation budget data over all local times, i.e. all solar zenith angles for the latitude range. Moreover, this instrument has gathered the only bidirectional radiance data covering all local times. An additional quartet of CERES instruments are now operating in pairs on both the TERRA and AQUA spacecrafts. Thus far, these instruments have collected several years of Earth radiation budget observations and continue to operate. For each of the TERRA and AQUA spacecrafts, one CERES instrument operates in a cross-track scan mode for the purpose of mapping the Earth's outgoing longwave radiation and reflected solar radiation. The other operates in an azimuthal rotation while scanning also in zenith angle for the purpose of gathering measurements for the angular distribution of radiance from various scene types, to improve the computation of fluxes from radiance measurements. The CERES instruments carry in-flight calibration systems to maintain the measurement accuracy of 1% for measured radiances. In addition to retrieving fluxes at the top of the atmosphere, the CERES program uses data from other instruments aboard the spacecraft to compute the radiation balance at the surface and at levels through the atmosphere. © 2003 COSPAR. Published by Elsevier Ltd. All rights reserved.

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1. Introduction

Weather and climate are determined by the temperature and motions of the atmosphere and oceans. This dynamic system is a heat engine which is driven by the absorption of solar radiation and the emission of outgoing longwave radiation at the top of the atmosphere. In order to understand weather and climate, measurements are needed for the energy which enters and leaves this system, i.e. the Earth with its atmosphere and oceans (Hartmann et al., 1986; Ramanathan, 1987; Ramanathan et al., 1989a). For this reason, a succession of satellite instruments have been developed and flown

(Smith, 1998). The Earth Radiation Budget Experiment (ERBE) was composed of scanning and non-scanning instruments, which provided radiation flux information at the “top of the atmosphere” (TOA) from November 1984 until October 1999 (Barkstrom and Smith, 1986; Barkstrom et al., 1989). From the ERBE data, researchers learned about the tremendous importance of clouds in regulating the radiation budget (Ramanathan et al., 1989b; Harrison et al., 1990). Thus, the Clouds and Earth radiant energy system (CERES) project was created to provide not only radiation fluxes at TOA as did ERBE but also to develop radiation fluxes at the surface and at levels throughout the atmosphere (Barkstrom, 1990; Wielicki et al., 1996). The CERES project also stipulated that the errors in the TOA fluxes would be reduced by a factor of 2. This need in turn required that the instrument errors be reduced by 2 and

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that the angular distribution models, which are required to compute flux from radiance measurements, be improved greatly.

The science objectives of the CERES project are:

1. to double the accuracy of estimates of radiation fluxes,
2. to provide a continuation of the Earth radiation budget record for climate,
3. to improve the angular distribution models (ADMs),
4. to provide estimates of radiative fluxes at the surface and within the atmosphere over the globe,
5. to provide cloud properties consistent with radiative fluxes from the surface to TOA.

In the following sections, the paper discusses CERES in the context of each of these objectives.

2. Instrument and continuation of radiation data

The CERES instrument was designed to be twice as accurate as the ERBE scanning radiometer. There are two fundamental requirements for an accurate instrument. First, the instrument must be well designed and constructed so as to have a low noise level and a gain change which varies with time slowly enough that any changes are small between calibration checks. Second, a calibration facility is needed to calibrate the instrument to the required accuracy. For a spacecraft instrument, calibration methods are required to maintain the calibration and must be used often enough that any change of calibration is small.

The CERES instrument was developed from the ERBE scanning radiometer (Kopia, 1986), with modifications based on experience with ERBE's use (Lee et al., 1996). Fig. 1 is a schematic representation of the CERES scanning radiometer. There are three telescopes mounted on a scanning beam, and this assembly is mounted to rotate in azimuth. The three telescopes provide measurements of shortwave, total and 8–12 μm

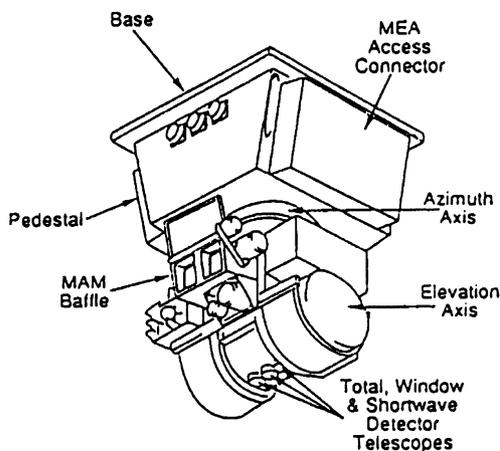


Fig. 1. View of CERES scanning radiometer.

window radiances. A calibration facility built by the prime contractor, TRW, uses a blackbody to tie the calibration of the three CERES channels to the International Temperature Scale of 1990 (Lee et al., 1998). Once in space, the calibration is maintained by use of on-board systems based on improvements to the ERBE systems (Lee et al., 2000; Priestley et al., 2000a,b, Barkstrom et al., 2000).

The CERES instruments are providing a continuation of the Earth radiation budget data record. The Proto-Flight Model (PFM) flew on the TRMM spacecraft and operated from December 1997 through September 1998. In-flight calibration checks verified that the calibration on ground and in space changed less than 1/2% (Smith et al., 1998). Because of a problem with the power supply, PFM was turned off in September 1998. Flight Models 1 and 2 went into space aboard the TERRA spacecraft on 18 December 1999 and began operating in February 2000. The two instruments alternate in scanning across-track to collect data about the geographic distribution of radiation, with the other operating usually with a biaxial rotation to gather information about the angular distribution radiance. The TERRA satellite is in a Sun-synchronous orbit with an Equator crossing at 22:30 h for the ascending node. In March 2000, the CERES PFM aboard the TRMM spacecraft was turned back on and operated until it failed in June 2000.

Although brief, the overlap period in 2000 between the TRMM and TERRA CERES instruments assured continuity in the measured climate data. Flight models 3 and 4 have been in orbit aboard the Aqua spacecraft since 4 May 2003. As with the two instruments on TERRA, FM-3 and -4 operate in a manner to collect data about the spatial and directional distribution of radiation. At present, all instruments on TERRA and AQUA are operating nominally and providing measurements of radiation at four local times each day for each region.

In order to use data sets from successive instruments for climate research, it is highly desirable that the data sets overlap. Otherwise, small changes in the record may be due to either changes in the instrument or changes of the climate variable. The Earth Radiation Budget (ERB) instrument aboard the Nimbus-7 spacecraft (Smith et al., 1977, Jacobowitz et al., 1984), together with the ERBS provide overlapping data sets for the period from October 1978 through September 1999. Kyle et al. (1990) found that the ERB/Nimbus-7 and ERBE/NOAA 9 global-mean shortwave and longwave fluxes agree to better than 0.5%. Green et al. (1990) demonstrated that the scanning and wide field-of-view radiometers aboard the ERBS agreed to better than 1% for the means. Rutan et al. (1999) intercompared ERBE wide field-of-view measurements with the CERES/TRMM measurements during 1998.

From March to June 2000, the CERES/TRMM was rotated in azimuth during orbit crossing with the

TERRA spacecraft such that the CERES/TRMM and either FM-1 or FM-2 viewed the same scenes from the same angles. Szewczyk (2002) intercompared these radiances and demonstrated that CERES/TRMM radiance measurements agreed with the TERRA, FM-1 and -2 CERES radiance measurements to better than 1% with a 95% confidence level for all channels, with the mean differences being less than 0.5%.

The TERRA and AQUA orbits cross at 70°N on the day side and at 70°S on the night side. In order to get a good radiance intercomparison, one of the CERES/TERRA and one of the CERES/AQUA instruments were rotated in azimuth as the spacecraft crossed 70°N so as to scan in an east–west direction. Thus, the same scenes were viewed from the same directions. In order to get good solar illumination of the scene so as to check the shortwave responses of the shortwave and total channels, the intercomparisons were done during early July 2002 when the solar declination was still high. These results are currently being analyzed. The Earth

radiation budget data sets now cover from October 1978 through December 2002 (as of this writing) to give nearly a quarter of a century of data with overlapping data sets as shown in Fig. 2. This period now covers two cycles of a decadal oscillation.

3. Data processing

The science objectives of CERES require the retrieval of radiant fluxes at the “top of the atmosphere,” the surface and at various levels within the atmosphere. Fig. 3 is a simple flow chart of the resulting data processing system, which is described more completely by Wielicki et al. (1998). There are three major types of products: “ERBE-like”, surface, and atmospheric. Also, after sufficient CERES radiance data have been compiled, approximately 8 months to 2 years of measurements, the radiances are used to develop ADMs, after which improved TOA fluxes are computed.

4. Angular distribution models

The major error in instantaneous fluxes is not due to errors in the radiance measurements, but is due to the ADMs which are required to compute fluxes from measured radiances. After averaging over space (to form regional averages on a grid) and time (to form daily and monthly averages), there is still a residual error due to the ADMs. Thus, the improvement of radiative flux products requires an improvement in the ADMs. The ADMs which were used to process ERBE data and

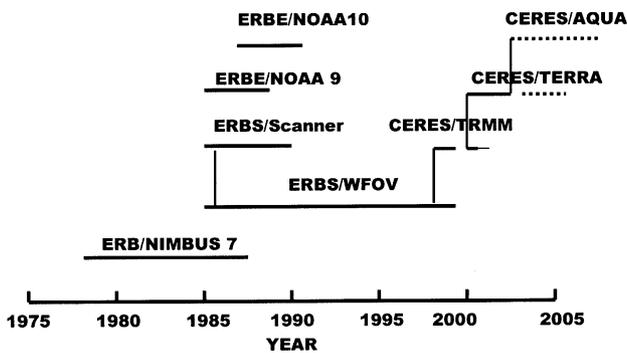


Fig. 2. Time line of ERB, ERBE and CERES observations.

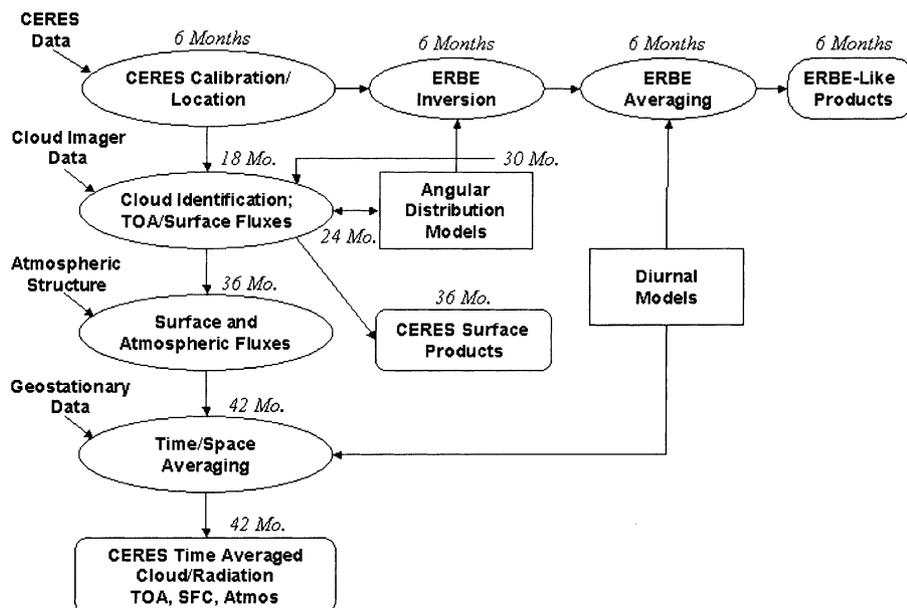


Fig. 3. Flow chart of CERES data processing. Ovals represent algorithm processes, boxes represent archived data products.

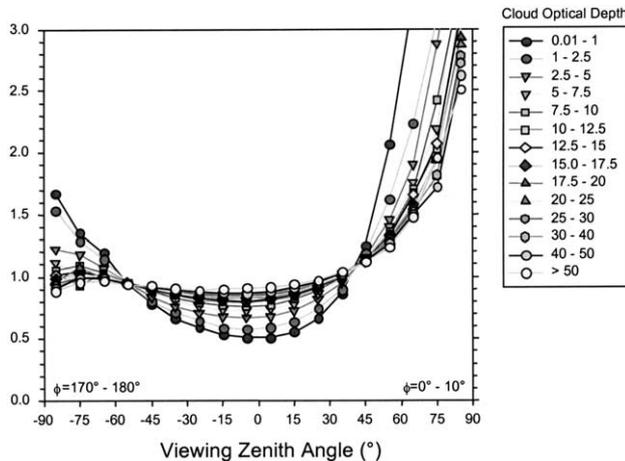


Fig. 4. Angular distribution models for ice clouds over ocean for varying optical thicknesses. Solar zenith angle ranges from 60° to 70° , near the principal plane.

which are used in a part of the CERES data processing (the “ERBE-like” products) are for 12 scene types and are based on 208 days of measurements from the ERB instrument aboard the Nimbus-7 spacecraft (Taylor and Stowe, 1984; Suttles et al., 1988, 1989). The CERES instrument was designed to operate with the azimuthal plane rotating while scanning in the nadir angle. Due to orbit constraints, not all combinations of view zenith angle and applicable relative solar azimuth and zenith angles are measured for each scene from a Sun-synchronous orbit. The CERES aboard the TRMM in its precessing orbit was operated in a 3-day duty cycle in which it scanned cross-track 2 days to provide maps of radiation flux and the third day it scanned with azimuthal rotation as well as nadir angle rotation for ADM data. Approximately 80 days of radiance measurements using biaxial rotation were thus collected. These data are unique because they are the only such data from a precessing spacecraft which include, e.g. measurements of reflected sunlight near tropical sunrise or sunset. The CERES/TERRA instruments have collected data in biaxial rotation for 3 years and the CERES/AQUA instruments have collected data for 6 months. These radiance measurements provide a greatly expanded data base from which to develop improved ADMs. In order to fill data sparse parts of an ADM, radiative transfer codes are needed. In the nearly 2 decades since the ERBE ADMs were created, radiative transfer codes and the computer capacity to apply them have improved vastly. To make major improvements in ADMs, it was necessary to increase greatly the number of scene types, especially to account for the variety of cloud types. In the last 2 decades, much progress has been made in spacecraft instrumentation and techniques for retrieval of cloud particle phase, optical depth, etc. As a consequence of these advances, a set of ADMs has been developed which reduces the errors in retrieved

instantaneous fluxes by a factor of 2 in some cases. With the improved ADMs, instrument error becomes important for long-term averages over large areas. There are ADMs for approximately 200 scene types for CERES (Loeb et al., 2003a,b), to replace the 12 for ERBE. Whereas for ERBE we had one model for overcast, for CERES there are a number of models for varying optical depth for ice cloud over ocean as shown by Fig. 4. The ADMs for clear sky over ocean for CERES contain wind speed as a parameter.

5. ERBE-like products

Data products for TOA fluxes as nearly identical as possible to those from ERBE are generated by the flow across the top of the chart shown in Fig. 3. These fluxes are computed by use of the ERBE ADMs (Suttles et al., 1988 and 1989) and using the ERBE time interpolation and averaging algorithms (Brooks et al., 1986). These products are produced so that they will be comparable to those from the ERBE data set, with minimal differences due to algorithm differences and thus useful for climate studies. These data products include individual pixel data with radiances and fluxes, daily average and monthly-mean regional fluxes and are made available quickly.

6. Surface radiation budget

In the vertical stream of Fig. 3, cloud data are brought in from the Visible and InfraRed Spectrometer (VIRS) on the TRMM and from the Moderate Resolution Imaging Spectrometer (MODIS) on the TERRA and AQUA spacecraft for the purpose of defining cloud optical depth, as well as particle type and size. From these results, surface fluxes are computed using fast algorithms for the surface-only fluxes, which are spatially gridded and averaged to produce regional-mean fluxes, then temporally averaged to produce monthly-mean regional surface fluxes.

The Li et al. (1993) algorithm uses the TOA reflected shortwave flux and precipitable water to derive the net shortwave flux at the surface. A second technique, described by Gupta et al. (2001), is also used to compute the net shortwave fluxes at the surface as well as the downward and upward shortwave fluxes.

For the longwave clear sky case, the downward, upward and net longwave surface fluxes are computed by the method of Inamdar and Ramanathan (1994) using the CERES broadband and 8–12 μm window radiance measurements, surface temperature, temperature profile, precipitable water and aerosol visible optical depth. The Inamdar and Ramanathan method also uses the surface emissivity maps developed by Wilber et al. (1999). For

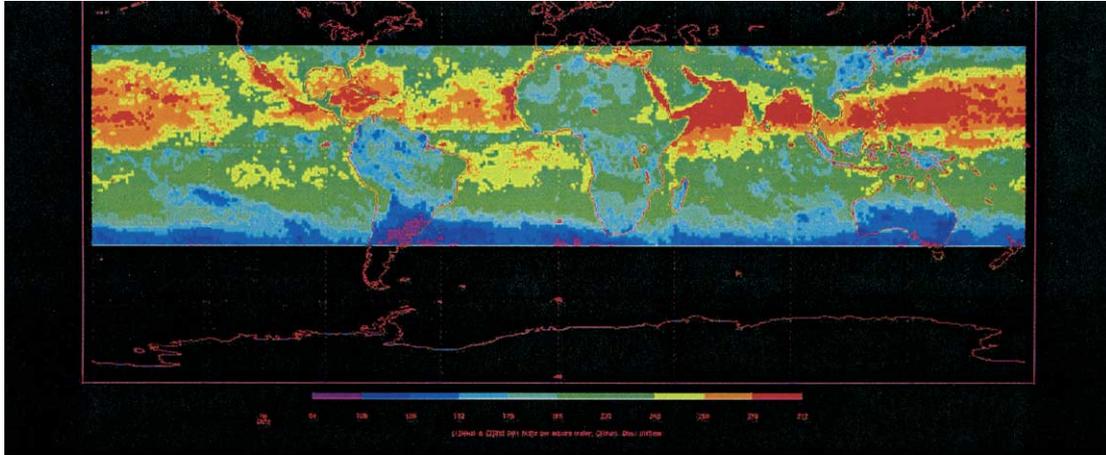


Fig. 5. Monthly-mean net longwave surface radiation fluxes for April 1998.

all-sky conditions, a second technique, described by Gupta (1989), is used to compute downward, upward and net surface longwave. Fig. 5 shows the monthly-mean net longwave surface radiation fluxes for April 1998.

7. Atmospheric radiation products

Profiles of temperature and humidity and cloud properties together with the measured radiances are used to generate fluxes at selected levels within the atmosphere, including the surface, for each CERES footprint (pixel), using a comprehensive radiative transfer code (Fu and Liou, 1993) which has been extensively modified (Rose and Charlock, 2002). These input data are varied by a constraint algorithm (Rose et al., 1997) according to their uncertainties such that the computed TOA radiances match the CERES measurements within their uncertainties. The result of this procedure is to provide cloud properties which are consistent with the radiative fluxes from the surface to TOA, as required by the last science objective stated in the introduction. These footprint fluxes are gridded and spatially averaged to produce instantaneous regional-mean fluxes, which are interpolated to synoptic times for use with circulation model results and

radiosonde measurements and finally temporal averaged to produce monthly products. Fig. 6 shows the mean radiative flux convergence between the surface and 500 mb for April 1998 as computed from CERES/TRMM measurements. The methods used in generating these products are new; thus much validation is required and additional time is needed before their release. The validation program includes the CERES Ocean Validation Experiment and the CERES ARM Validation Experiment; information about this work is available on-line at <http://www-svg.larc.nasa.gov>.

One source of error in computing daily-mean and monthly-mean fluxes is the interpolation of flux values between measurements. This time-sampling error is reduced for CERES by using data from geostationary meteorological satellites. The CERES measurements are “anchor” points and the geostationary data provide the variation of fluxes between these points.

8. Looking ahead

The CERES Flight Model 5 has been built and calibrated. At present, this instrument is ready to fly and is available for a spacecraft of opportunity. An ideal mission would be on a precessing satellite, so

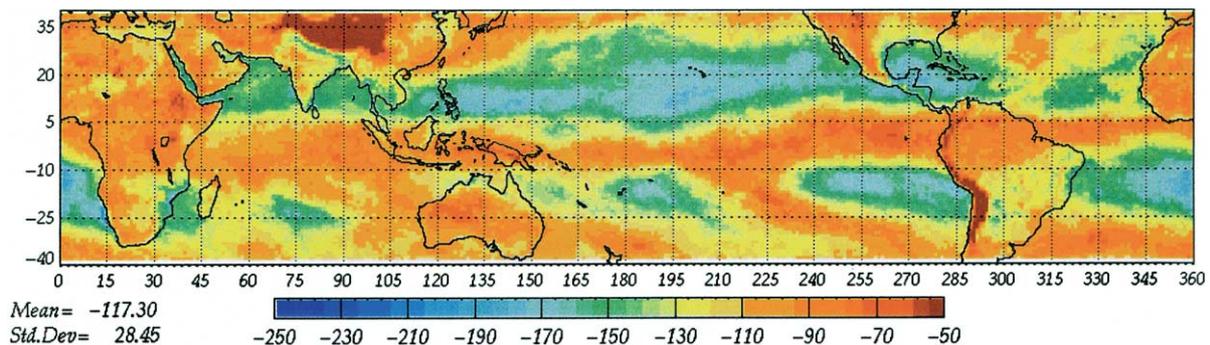


Fig. 6. Mean radiative flux convergence between the surface and 500 mb for April 1998 as computed from CERES/TRMM measurements.

that more biaxial rotation measurements could be gathered over all times and solar zenith angles for the latitude range to improve angular distribution models for radiance and reduce errors in computed fluxes.

The Geostationary Earth Radiation Budget (GERB) instrument has begun operating on the MeteoSat Second Generation satellite. From its position near latitude and longitude zero, it provides excellent temporal coverage of that sector of the globe. There are a number of synergisms between the CERES and the GERB. Intercomparisons of data products at various levels will provide validation for these data. For example, intercomparisons of radiances will help to validate both instruments. The GERB will provide information regarding the temporal interpolation and averaging of CERES data products.

What are the continuing needs for radiation budget measurements after the CERES program? Weather and climate are dynamic and always changing over a wide range of time scales. There are a number of climate variations which are important socially and economically. In order to understand the processes which cause these changes, it is usually necessary to have information about the energetics as driven by radiation. In order to meet the ongoing need for accurate radiation measurements, the Earth Radiation Budget Suite is planned for flight on the National Polar-orbiter Operational Environmental Satellite System. There is a concern that there will be a gap of radiation budget measurements between the TERRA and AQUA instruments now operating and the instrument aboard the NPOESS spacecraft, so that the continuous data record provided by the overlapping data sets will be ended.

9. Getting CERES data

CERES and ERBE data can be obtained from the Atmospheric Sciences Data Centre of Langley Research Centre at <http://eosweb.larc.nasa.gov>. CERES documentation is available at <http://asd-www.larc.nasa.gov/ceres/docs.html>.

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