Clouds and the Earth’s Radiant Energy System (CERES): An Earth Observing System Experiment

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ABSTRACT

Clouds and the Earth’s Radiant Energy System (CERES) is an investigation to examine the role of cloud/radiation feedback in the Earth’s climate system. The CERES broadband scanning radiometers are an improved version of the Earth Radiation Budget Experiment (ERBE) radiometers. The CERES instruments will fly on several National Aeronautics and Space Administration Earth Observing System (EOS) satellites starting in 1998 and extending over at least 15 years. The CERES science investigations will provide data to extend the ERBE climate record of top-of-atmosphere shortwave (SW) and longwave (LW) radiative fluxes. CERES will also combine simultaneous cloud property data derived using EOS narrowband imagers to provide a consistent set of cloud/radiation data, including SW and LW radiative fluxes at the surface and at several selected levels within the atmosphere. CERES data are expected to provide top-of-atmosphere radiative fluxes with a factor of 2 to 3 less error than the ERBE data. Estimates of radiative fluxes at the surface and especially within the atmosphere will be a much greater challenge but should also show significant improvements over current capabilities.

1. Introduction

Mankind is engaged in a great and uncontrolled alteration of his global habitat. Fossil fuel burning and the release of other trace gases and aerosols are expected to have long-term consequences. Agriculture and deforestation alter the earth’s surface in ways that are expected to change the climate. In these and many other examples, the immediate impact of man’s activities are understood, yet the long-term consequences cannot be predicted. One of the major sources of uncertainty lies in the impact of clouds upon the radiative energy flow through the earth–atmosphere system. For example, an intercomparison of 19 climate general circulation models shows a factor of 3 to 4 variation in the modeled sensitivity of the earth’s climate (Cess et al. 1990). The source of this variation was traced to the different parameterizations of clouds in the GCMs. In some models, clouds acted as a strong positive feedback mechanism, in others as a strong negative feedback mechanism. The reason for such large uncertainties is the primitive state of cloud modeling in climate models. GCM climate models are limited to horizontal spatial scales of hundreds of kilometers, while most cloud physical processes operate on much smaller scales (down to 100 m).

In recent years, the Earth Radiation Budget Experiment (ERBE) has measured the flow of radiation at the top of the atmosphere (TOA), not just as an undifferentiated field, but with a separation between clear-sky fluxes and cloudy ones (Wielicki and Green 1989). These clear-sky fluxes begin an observational baseline for assessing the impact of changes on the earth’s surface. Cloud radiative forcing (i.e., total-scene radiation minus clear-sky radiation) determines the effect of clouds on the radiation budget (Charlock and Ramanathan 1985; Ramanathan et al. 1989; Harrison et al. 1990). For example, in the current climate system, the longwave (LW) radiative forcing of cloud systems nearly offsets the shortwave (SW) cloud forcing over much of the Tropics. Large negative cloud forcing is found over the storm tracks at middle to high latitudes in the summer hemisphere, where

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cloud albedo effects outweigh greenhouse effects. The most extreme cloud cooling effects occur over marine areas, since the contrast in albedo between clear and cloudy conditions is greatest over oceans. On average, clouds have a cooling effect on the earth for all seasons (Harrison et al. 1990).

Beyond measuring the TOA fluxes, there is a need to develop the ability to measure the entire radiative energy flow within the earth–atmosphere system consistently, with a simultaneous quantification of the clouds. This ability would provide both radiative fluxes at the surface and the atmospheric radiative flux divergence, which enters directly into physically based, extended-range weather and climate forecasting. Increased understanding of these processes could lead to improvements of our capabilities for long-range weather and climate forecasting, which could have large economic impacts. GCM modeling studies (Randall et al. 1989) indicate that while TOA cloud radiative forcing may be near zero in the Tropics, the cloud radiative forcing within the atmosphere is large and plays a critical role in driving the Hadley cell circulation. Knowledge of clouds and radiation would also provide the surface radiation budget, which is critical to studies of atmospheric energetics, air–sea energy transfer (Liu and Gautier 1990), and biological productivity.

2. CERES Origins

The National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) is part of an international program for studying the earth from space using a multiple-instrument, multiple-satellite approach. The EOS mission is to advance the understanding of the entire earth–atmosphere system through comprehensive observations and interdisciplinary analyses of the data. The Clouds and the Earth’s Radiant Energy System (CERES) experiment provides the radiation data for EOS.

The CERES instrument is designed to provide a climate dataset suitable for examining the role of clouds in the radiative heat balance of the climate system. The CERES experiment is an extension of previous measurements of the earth’s radiation budget from satellites. Flat-plate radiometers on Nimbus-6 and Nimbus-7 provided a very coarse spatial and temporal resolution data record. Higher-spatial-resolution scanning instruments on Nimbus-3, Nimbus-7, and most recently the Earth Radiation Budget Experiment and the Scanner for Radiation Budget have obtained global measurements of outgoing broadband shortwave and longwave radiation at the top of the atmosphere. In general, each of these instruments provided successively higher spatial resolution, increased accuracy, and longer time records of this critical climate variable. Analysis of the most recent ERBE data has confirmed the critical role played by clouds in controlling the regional and global radiation budget of the earth. This recent analysis, along with the experience of the CERES Science Team members in international and national projects such as the International Satellite Cloud Climatology Project (ISCCP), the First ISCCP Regional Experiment (FIRE), and the Surface Radiation Budget Project supplied the impetus and direction for the CERES project. CERES estimates not only TOA radiative fluxes but is also used in conjunction with more complete cloud properties from other EOS instruments such as the Moderate-Resolution Imaging Spectroradiometer (MODIS) to determine radiative fluxes within the atmosphere and at the surface.

The CERES Science Team blends expertise in broadband radiometry, cloud and radiation remote sensing, and climate modeling. The science team guides the definition of the CERES instrument and science studies. The science team for CERES/EOS is led by an instrument principal investigator (PI) for the instrument, algorithms, and data system (CERES-I) and an interdisciplinary science PI to study the CERES data in conjunction with other EOS datasets and climate models [CERES-Interdisciplinary Science (IDS)]. B. Barkstrom of the NASA/Langley Research Center is the CERES instrument PI, and B. Wielicki, also from NASA/Langley, is the CERES interdisciplinary science PI. The Science Team coinvestigators are as follows:

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3. Instrument concept

The CERES instrument (Fig. 1) consists of a three-channel scanning broadband radiometer, which uses precision thermistor bolometers to achieve radiometric measurements with high accuracy and stability (Cooper et al. 1992). The CERES instrument is a new design based on the successful ERBE scanning radiometer (Kopia 1986), with several improvements to accommodate upgraded performance requirements and hardware developments. CERES radiometers (Fig. 2) consist of a precision thermistor bolometer detector located near the focus of the secondary mirror of a Cassegrain telescope with an 18-mm aperture. Mirrors are silver coated to provide broadband spectral flatness. Each radiometric channel incorporates a matched pair of precision thermistor bolometers in a bridge network to measure radiant flux. One bolometer serves as an active signal detector and the other as a compensator for heat-sink thermal variations and long-term aging effects. The thermistor bolometers have a time constant of about 8 ms, including the effects of a black paint (custom designed to enhance spectral flatness), which covers the active area of the bolometer. Advances in the time response of the thermistor bolometers allow the CERES field of view to be reduced to 20 km, about a factor of 2 smaller than that for ERBE. A hexagonal-shaped field stop establishes the 1.3° × 2.6° field of view and minimizes aliasing effects. Improvements in electronic design allow a longer instrument lifetime and reduce electronic noise in the measured radiances.

Because the objective of CERES includes surface and atmospheric radiative fluxes (as well as TOA fluxes), one of the three spectral channels measures the thermal radiation emitted from the earth’s surface in the 8–12-μm “window.” The window channel is expected to improve the estimates of clear-sky longwave flux at the surface (especially over nonblack land surfaces) and can allow a well-calibrated separation of window and nonwindow atmospheric green-
house effects, which are a strong function of latitude (Inamdar and Ramanathan 1995, manuscript submitted to Tellus). An additional reason for replacing the ERBE broadband longwave channel is the lack of any spectrally flat broadband longwave filters covering the spectral range of 5–50 \( \mu \text{m} \).

The remaining two CERES spectral bands measure shortwave (0.2–5 \( \mu \text{m} \)) and total (0.2–100 \( \mu \text{m} \)) broadband radiation. Broadband longwave radiation is estimated as the total minus the shortwave, the same technique used on ERBE. The three telescopes are co-aligned such that they share a 98% common field of view. The CERES scanner operation is illustrated in Fig. 3. One 6.6-s scan cycle consists of a scan from space beyond the earth limb (at 18°) across the earth to space on the opposite side (162°), then a quick scan to a brief pause at the internal calibration sources (194°), then back to space (162°), and a scan back across the earth to space on the opposite side (18°). Instrument pointing accuracy is about ±0.25°. Figure 4 shows the elevation scan-cycle profile. Internal calibration sources consist of blackbodies, which include integral platinum resistance thermocouples and heaters for calibration against a range of blackbody temperatures. For the shortwave channel, a tungsten filament lamp and collimating optics provide a multilevel stimulus on command. For solar calibration, a special mirror attenuator mosaic (MAM) reduces the solar intensity to within the range of the SW and total channels. Internal and solar calibrations are performed every two weeks. The CERES instruments are being developed by TRW's Space and Technology Group in Redondo Beach, California, under contract to the NASA/Langley Research Center. Schaeffer Magnetics, Incorporated and Servo Corporation of America are major subcontractors to TRW, providing key subsystems of the instrument. In October 1995 the first CERES scanner successfully completed ground calibration and was shipped to Goddard Space Flight Center for integration on the Tropical Rainfall Measuring Mission (TRMM) spacecraft.

4. Instrument calibration and other error sources

Experience with ERBE observations has shown that the errors in measuring radiative fluxes from space are dominated by three components. The first source of error in estimates of the earth's radiation budget is instrument calibration (Jarecke et al. 1993; Folkman et al. 1994) and stability. The ERBE scanners on which the CERES design is based have demonstrated stability and internal consistency at less than 1% over a period of 5 years (Lee and Barkstrom 1991). The fundamental traceability of CERES data to absolute standards is established by ground calibration. The CERES absolute radiometric calibration facility (Fig. 5) provides calibration of each instrument over its full spectral range, field of view, and dynamic range. The cryo-pumped calibration chamber is a vacuum chamber with a liquid nitrogen shroud to simulate the space environment. The
CERES instrument is mounted on a carousel that can rotate 360° as well as move vertically over 12 in. The carousel positions the instrument at one of several stations where calibrations and performance tests take place. At each end of the 8-ft-diameter chamber is a door-mounted, temperature-controlled disk. At one end of the chamber are blackbodies, which provide the longwave calibration. A shortwave reference source is located at the opposite end of the chamber. Cryogenically cooled blackbodies provide constant space reference sources at each end of the chamber to ensure a known temperature for the simulated space-look portion of the scan cycle. Also included in the calibration chamber are a point-spread function-measurement source and a constant-radiance reference (CRR) source to permit assessment of potential scan-dependent variations and a solar simulator to simulate solar calibration with the MAM. The absolute radiometric calibration facility is operated by a computer-based control system. CERES goals for calibration are 0.5% for LW and 1% for SW radiation (Lee et al. 1996).

A second source of error is insufficient sampling of the angular variation of radiation. The cross-track scanning pattern required for good spatial sampling over the globe gives limited and biased sampling of angular space. Ideally, observations of radiation are required from all viewing angles of a region on the earth. For this reason, the first two Earth Observing System satellites (EOS-AM and EOS-PM) include two CERES scanners, one in cross-track scan mode for optimizing spatial sampling and obtaining global coverage and a second instrument with a rotating azimuth scanner for improved angular sampling. The rotating azimuth plane scanner samples the full range of viewing angles (when composited over time) and is used to generate greatly improved models of the angular variation of radiation. The CERES scanner aboard the TRMM scans while rotating in the azimuth plane for a portion of its time in order to get radiation measurements for the full range of solar zenith angles at low latitudes. The rotating azimuth scanner data provide two types of angular models: an angular model required to convert radiance to flux, and a model of the solar zenith angle dependence of albedo required to compute diurnal averages of solar fluxes (Suttles et al. 1988). These new angular models are expected to reduce errors in the radiation budget data by factors of 2 to 4 for both bias and rms errors of SW and LW TOA fluxes.

The third source of error is the inability to adequately sample the large diurnal variation of solar-reflected and earth-emitted radiation. Simulation studies using Geostationary Operational Environmental Satellite hourly data indicate that time-sampling errors will be reduced significantly by flying CERES instruments simultaneously on multiple satellites (EOS-AM, EOS-PM, and TRMM). For example, two satellites reduce the time-sampling errors in the monthly mean shortwave radiation by 55% over that of a single satellite, and with three satellites the error is reduced by 78%. TRMM will be launched in 1997, EOS-AM in 1998, and EOS-PM in 2000. EOS-AM and EOS-PM will be replaced every 6 years to provide an 18-yr data record. TRMM follow-on missions are also being discussed jointly with the Japanese National Space Development Agency.

Table 1 gives an estimate of the CERES error budget for TOA net radiative flux averaged monthly over equal-area regions of the earth (1.25° lat × 1.25° long at the equator). Given accurately calibrated radiom-
eters (1% or better), the angular-sampling and time-
(diurnal) sampling error sources dominate the CERES
regional error budget, while the instrument calibration
derror dominates the global average error. The im-
proved angular and temporal sampling of the CERES
experiment will improve the accuracy of the data re-
etive to ERBE by a factor of 2 to 3, depending on the
time and space scales of interest. Similarly, ERBE
improved accuracy by about a factor of 2 over that
achieved by the *Nimbus-7* ERB. Error estimates are
taken from several studies using *Nimbus-7* and ERBE
data (Suttles et al. 1988, 1992; Harrison et al. 1990;
Green et al. 1990; Barkstrom et al. 1989, 1990). The
science requirements were taken from a workshop on
the earth radiation budget (Stowe 1988).

A final question of interest is the ability of the
CERES data to detect long-term trends. In this case the
question is not one of ab-
solute accuracy, but of relative stability
and noise level. Consider the case of a
1.25° lat × 1.25° long “box” for which
TOA fluxes have been obtained for the
month of July in a sequence of 10 years.
What level can trends in the radiation
budget at the TOA be detected by the
planned CERES measurements? The angular-
and time-sampling errors given in
Table 1 are primarily systematic for
a given place on the earth with a given
climatology. Since the satellite orbit
sampling in time and viewing angle are
the same from year to year, the result-
ing time- and angular-sampling errors
are stable and should have little effect on

### TABLE 1. CERES error budget: TOA net flux and equal-area regions (1.25° lat/long
at the equator) in a three-satellite system. Errors are given in units of watts per square
meter.

<table>
<thead>
<tr>
<th>Source of error</th>
<th>Monthly average global bias</th>
<th>Monthly average regional, 1σ</th>
<th>Daily average regional, 1σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular sampling</td>
<td>0.9</td>
<td>1.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Time sampling</td>
<td>1.1</td>
<td>2.3</td>
<td>8.1</td>
</tr>
<tr>
<td>Instrument calibration</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Total</td>
<td>2</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Science requirement</td>
<td>0.2–1</td>
<td>2–5</td>
<td>5–10</td>
</tr>
</tbody>
</table>

Given the discussion above, there are five major
measurement objectives for the CERES experiment
and complementary imagers aboard the satellites.
These objectives are described in terms of output
products in Table 2. Satellite overpass output pro-
ducts are given at the CERES field of view resolution
(20 to 50 km), while all 3-h synoptic, daily, monthly,
and yearly average products are output on the CERES

### TABLE 2. Major measurement objectives for CERES and complementary imagers.

<table>
<thead>
<tr>
<th>Output products</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top-of-atmosphere radiative fluxes</td>
<td>SW, LW (up)</td>
</tr>
<tr>
<td>Angular-dependence models of solar and thermal infra-red radiation</td>
<td>SW, LW, vary with surface and cloud condition</td>
</tr>
<tr>
<td>Cloud properties</td>
<td>Amount, height, thickness, SW and LW optical depth, particle size, particle phase</td>
</tr>
<tr>
<td>Atmosphere radiative fluxes</td>
<td>SW, LW (up, down, net)</td>
</tr>
<tr>
<td>Surface radiative fluxes</td>
<td>SW, LW (up, down, net)</td>
</tr>
</tbody>
</table>
equal-area (140 km x 140 km) grid. The CERES instrument measures TOA fluxes and provides data for developing angular dependence models. For TOA fluxes, an ERBE-like processing method is used to ensure continuity between the ERBE and CERES datasets. In addition, an improved estimate of TOA fluxes is made using the more advanced cloud identification and angular-dependence models provided by CERES. The new angular-dependence models will be a composite of CERES observations over a complete range of viewing and solar illumination angles. The models are a function of both surface type and cloud properties. Cloud information is produced by the CERES team, using EOS imaging and sounding instruments such as MODIS on EOS or the Visible Infrared Scanner (VIRS) imager on TRMM. Figure 6 gives a flow chart of the data processing system required to convert satellite-measured radiances into estimates of radiative fluxes and cloud properties. A brief description of the analysis methods is given in sections 5a–d below.

Availability of the data products will be phased in time as a result of the varying complexity of the post-launch validation of the data products. The validated ERBE-like TOA flux data product is expected to be available starting 6 months after launch. Gathering sufficient CERES data to develop new angular-dependence models, along with validation of cloud properties, surface radiative fluxes, and in-atmosphere fluxes, is expected to take approximately 2 years after launch. Preliminary test datasets, however, will be available much earlier than the final validated datasets. As for ERBE, radiative flux data will be determined both for clear-sky only and total-sky conditions.

a. Cloud properties

At present, the ISCCP is the most sophisticated cloud analysis applied routinely to a global dataset (e.g., Rossov et al. 1993). The ISCCP provides estimates of cloud fraction, cloud-top height, and cloud optical depth. ISCCP algorithms are based upon a bispectral threshold algorithm applied to samples of geostationary satellite data, with the use of polar orbiter data when the geostationary data are not available. The cloud/clear threshold values are chosen after time-filtering radiances from the 5- to 30-day period before the threshold is applied. The ISCCP deduction of cloud properties other than areal coverage is based on theoretical models of radiative transfer, using a table lookup procedure. The ISCCP products are still being validated, using intensive field observations including the FIRE and the International Cirrus Experiment field programs. The capabilities of the EOS cloud-imaging instruments such as MODIS enable CERES to expand upon the ISCCP capabilities in several critical areas.

- Polar clouds—A combination of spatial texture measures (Ebert 1987; Welch et al. 1988) and spectral bands sensitive to cloud/snow/ice particle size (1.6-, 2.1-, and 3.7-µm channels) improves polar cloud retrievals.
- Boundary layer clouds—Higher spatial resolution data (0.25 versus 8 km) and spatial texture measures (Coakley and Bretherton 1982) allow more accurate cloud determination, especially for cumulus clouds.
- Multiple cloud levels—Sounding channels are used to isolate upper-level thin cirrus from boundary layer clouds detected using window channels (Baum et al. 1994).
- Cloud particle size/phase—Cloud particle size (Hansen and Pollack 1970; Nakajima and King 1990) is estimated using solar reflectance channels (0.66, 1.6, 2.1, and 3.7 µm) during the day; night-
time estimates are obtained using thermal infrared (3.7, 8.5, 11, and 12 μm) channels (Prabhakara et al. 1988; Luo et al. 1994).

- Cloud optical depth—Estimates for upper-tropospheric optically thin clouds use thermal infrared channels (Wielicki and Coakley 1981), while lower-tropospheric clouds and optically thick clouds use solar channels (Nakajima and King 1990). Cloud particle size and phase are used to relate solar and infrared optical depths.
- Cloud water/ice path—Cloud optical depth, cloud height, and cloud particle size/phase are used to estimate the areal density of cloud water and ice. Cloud thickness determination (top height minus base height) depends on cloud water/ice path estimates (Minnis et al. 1992, 1993a,b).
- Clear-sky conditions—Spatial texture measures (Coakley and Bretherton 1982) and spectral signatures will be added to the time-filtering techniques used by the ISCCP. Improvements are also possible because of higher spatial resolution data.

Cloud retrieval instruments include the MODIS on the EOS satellites and the Visible Infrared Scanner (VIRS) instrument on the TRMM. Cloud properties are determined separately for each CERES 20-km field of view, as well as composited to regional, zonal, and global scales.

b. Top-of-atmosphere fluxes

Scanning radiometers that observe the earth measure radiances, as opposed to the desired fluxes. Angular dependence models (ADMs) define an anisotropic factor $R$ to convert radiance into an estimate of flux, such that

$$ R = \frac{\pi I}{F}, \quad \frac{\pi I}{F} $$

where $I$ is the measured broadband radiance in W m$^{-2}$sr$^{-1}$ and $F$ is the radiative flux in W m$^{-2}$. For a Lambertian surface, $R$ is equal to 1. Anisotropy is greatest for shortwave radiation, where values of $R$ commonly vary from 0.5 to 2.0. Anisotropy for longwave radiation varies between about 0.7 and 1.2. Shortwave anisotropy varies not only with solar zenith angle, viewing zenith angle, and azimuth angle, but also as a function of both surface type (ocean, desert, land vegetation) and cloud condition (fraction, optical depth, particle size and phase, 3D cloud structure). Longwave anisotropy varies as a function of atmospheric state (temperature lapse rate, water vapor) and cloud properties (fraction, height, optical depth, 3D cloud structure).

The most complete set of ADMs currently available for radiation budget studies were developed for the ERBE experiment using Nimbus-7 data (Suttles et al. 1988). The ERBE ADMs determine anisotropy as a function of cloud cover (Fig. 7) and four surface types (ocean, land, desert, snow/ice). There is no dependence in the ERBE ADMs, however, on cloud properties such as optical depth. Figure 8 shows the strong dependence of anisotropy on cloud optical depth, as derived from a radiative transfer model (Suttles 1981). Three-dimensional cloud structure (i.e., non-plane-parallel) is also expected to have a large impact on anisotropy (Davies 1984). For these reasons, CERES will expand the number of cloud ADMs beyond the simple four cloud cover classes provided by ERBE. Development of these new CERES ADMs requires simultaneous cloud imager and CERES rotating azimuth plane scanner observations. Cloud properties are derived within the footprint of each CERES scanner field of view using high spatial and spectral resolution MODIS (EOS) and VIRS (TRMM) data. This matched set of cloud properties and broadband radiances is used to derive the new CERES anisotropic models. Given the simplicity of the ERBE models, this process is likely to improve the accuracy of TOA flux estimates by a factor of 2 to 4.

c. Surface fluxes and atmospheric radiative divergence

While global, satellite-based climatologies of cloud properties and TOA fluxes first appeared about 20
FIG. 8. Theoretical shortwave anisotropic models for varying cloud optical depth over a black surface. Anisotropic factor $R$ is defined in (1).

years ago (most recently the ISCCP and ERBE), studies to remotely sense surface fluxes and atmospheric divergence have begun more recently (e.g., Pinker and Laszlo 1992; Darnell et al. 1992; Rossow and Zhang 1995; Li et al. 1995). These studies are critical, however, to understanding climate processes such as the seasonal cycle of ocean surface temperature (Liu and Gautier 1990) and the strength of the atmospheric Hadley cell (Randall et al. 1989).

Estimates of surface and atmospheric fluxes are inherently more difficult than TOA fluxes because of the need for more accurate information on the atmospheric state, surface, and cloud properties. One of the objectives of the CERES investigation is to improve these new estimates of broadband shortwave and longwave fluxes both at the surface and within the atmospheric column, initially at the tropopause and several levels in the stratosphere, then later at 500 mb and additional levels in the troposphere. The appropriate number of levels of tropospheric radiative fluxes will be determined by model sensitivity studies and by analyzing validation datasets collected by programs such as FIRE and the Department of Energy’s Atmospheric Radiation Measurement (ARM) program. The ARM program provides a wide range of observations useful for checking the consistency of within-atmosphere radiative fluxes for both clear-sky and cloudy conditions: temperature and water vapor vertical profiles (the Radio Acoustic Sounding System, radiosonde, and Raman lidar), aerosol optical depth, lidar and radar profiles of cloud properties, surface narrowband and broadband radiances and fluxes, and also campaigns with aircraft radiative flux measurements at selected atmospheric levels. The combination of the MODIS cloud/surface imaging and CERES broadband satellite data, along with the ARM surface-based observations, provides an unprecedented capability to address this problem.

Because obtaining surface fluxes is much more difficult than measuring TOA fluxes as in ERBE, CERES investigations are examining two independent approaches. First, simple parameterization methods are used to directly determine surface LW and SW fluxes from TOA data. These methods are based on establishing direct relationships between TOA radiative fluxes and surface fluxes and validating these parameterizations using actual surface radiative flux and TOA flux measurements (Davies et al. 1984; Cess et al. 1991; see Fig. 9). Li et al. (1993a) have developed TOA-to-surface flux parameterizations for shortwave clear conditions. This SW model has been validated using observational data from ERBE along with tower-based radiative observations of the surface (Li et al. 1993b). Methods for deriving downward LW flux under clear skies over ice-free oceans, using satellite-measured outgoing LW and column-integrated water vapor, have also recently been developed (Inamdar and Ramanathan 1995, manuscript submitted to Tellus; Stephens et al. 1994). For cloudy skies, the simple methods applied to clear-sky conditions are still under investigation (e.g., Cess et al. 1995; Li et al. 1995).

FIG. 9. Theoretical relationship of net (i.e., absorbed) shortwave flux at the top of the atmosphere compared to net shortwave flux at the surface (from Cess et al. 1991).
For the second method, cloud physical and narrowband radiative properties are determined using primarily cloud imager data such as MODIS on the EOS-AM and EOS-PM platforms and the Visible Infrared Scanner on the TRMM spacecraft. Using these cloud properties along with atmospheric temperature and humidity data, broadband radiative fluxes can be calculated at the surface of the earth, through the atmosphere, and up to the TOA. These calculations use observed cloud properties (such as cloud amount, height, radiating temperature at 11 μm, visible optical depth, cloud particle size, and phase) determined using the cloud imager footprints within the much larger CERES broadband radiometer footprint (about 20 km at nadir).

Radiative transfer models used in these calculations are similar to those used by GCMs. Current plans are to provide radiative flux calculations initially at the tropopause and at several levels in the stratosphere. Later work will add 500 mb and additional tropospheric levels, as warranted by validation studies. When estimates of surface and atmospheric radiative fluxes are integrated to the top of the atmosphere, comparisons can be made to the measured TOA fluxes. Consistency at the top of the atmosphere (an instantaneous CERES field of view constraint of < 15 W m⁻² in SW flux, < 5 W m⁻² in LW flux) is used to adjust the input cloud and atmospheric properties most likely in error. For example, for clear-sky LW fluxes over the ocean, atmospheric water vapor, the most likely error source, is adjusted once in order to avoid large numbers of iterations.

One of the most difficult problems is the case of determining surface downward longwave fluxes when there is a middle-level or upper-level optically thick cloud present. If a lower-level cloud is also present beneath this middle/upper cloud, the lower cloud cannot be seen with the cloud imager. The underlying cloud may, however, be detected using the passive microwave measurement of liquid water path (LWP) or a more sophisticated imager/microwave combined multichannel retrieval. Recent sensitivity studies using calculations on ISCCP data indicate that the largest uncertainty in the LW fluxes at the surface is not in estimating the thickness of an observed cloud to get cloud base from cloud top but in knowing the amount of cloud overlap—that is, the presence of multilayer clouds (Charlock et al. 1994). Thus, the interest is in using cloud-imager data (narrowband solar and thermal infrared radiometer) combined with data from a passive microwave radiometer, which is capable of penetrating the upper cloud level, while still responding to a lower water cloud. Because of the difficulty in deriving microwave LWP over land surfaces, this approach is currently limited to oceanic regions.

If calculations of radiative fluxes within the atmosphere are done with radiative models similar to those used in GCMs, then what are the advantages of the satellite-derived estimates over existing GCM calculations? There are several.

- The satellite flux calculations use observed cloud physical and radiative properties. Cloud physics is arguably one of the weakest parts of current GCM simulations (Houghton et al. 1990).
- The satellite flux calculations are constrained to match instantaneous CERES TOA flux measurements. In particular, this allows the satellite calculations to be adjusted to match the effects of non-plane-parallel clouds. The non-plane-parallel radiative effects are included in the TOA flux measurements through the use of the empirical angular-dependence models discussed in section 5a. The TOA flux constraint also allows the satellite calculations to correctly account for nonspherical ice particle scattering, which again is included in the empirical angular models.
- The satellite calculations incorporate more realistic spatial variations in cloud optical properties, thereby avoiding the radiative flux bias caused by the assumption of uniform cloud optical properties in a GCM grid box. Cahalan et al. (1994) have shown that this error can be as large as 10%–15% in cloud albedo, even for overcast stratocumulus cloud fields.
- The satellite flux calculations are also constrained by validation against direct measurements of surface radiative fluxes.

While the determination of surface and within-atmosphere radiative fluxes is clearly a major challenge, especially for overlapped cloud conditions, the above advantages indicate that even with these challenges, the satellite estimates are expected to be more accurate than estimates available from GCM simulations.

**d. Time interpolation and averaging**

At the heart of EOS as an observing system lies the concept of long-term observations over the complete earth, with adequate sampling of the temporal variability to reduce time interpolation errors. There are two major considerations in going from instantaneous
observations to time-interpolated synoptic values and in producing time-averaged values. The first of these is the selection of the best combination of satellite orbits for sampling in time and space (Harrison et al. 1983). The second involves the development of methods for time–space assimilation and interpolation across data voids (Harrison et al. 1994).

The first goal is achieved by the current plan of flying the CERES instrument on two sun-synchronous orbiters (EOS-AM at 10:30 A.M. and EOS-PM at 1:30 P.M.) and the TRMM in an inclined orbit. The local time sampling at each latitude is shown in Fig. 10 for these three platforms for one month of observations. The sun-synchronous EOS platforms provide observations at fixed times, and the precessing TRMM orbit covers the entire diurnal cycle in about 48 days. This time-sampling configuration provides excellent temporal coverage of the diurnal radiative cycle for most of the globe (Harrison et al. 1992, 1994).

To produce synoptic fields and daily and monthly averages of radiative parameters from the asynoptic CERES observations, care must be taken to accurately interpolate these parameters to times between the measurements. Two different methods of interpolation are used to accomplish this goal for CERES. The first technique employs the techniques used by ERBE to produce the most accurate estimates of monthly mean TOA flux currently available (Harrison et al. 1990). In addition, a second interpolation method will also be implemented that uses narrowband geostationary data to provide information about changes in meteorological conditions between CERES observation times.

The CERES baseline approach for both interpolation techniques is to treat each 140-km region independently of other regions, as done by ERBE. This approach relies upon the ability to construct a reasonable statistical estimate of regional time series based upon past observations, notably those of ERBE, ISCCP, and gridded meteorological products. For example, based on an examination of geostationary data, ERBE assumed that the variation of clear-sky longwave TOA flux over desert regions varies as a half cosine (nearly constant at night, cosine with peak near noon during the day) (Brooks et al. 1986; Harrison et al. 1988). This functional form was then used to interpolate between ERBE observations at varying times of day. Over oceans, linear interpolation was used for longwave radiation. For TOA solar reflected radiation, models of the variation of albedo as a function of solar zenith angle are employed to interpolate between daytime observations. The ERBE albedo models are a function of cloud condition (i.e., clear, partly cloudy, mostly cloudy, overcast) and surface type (i.e., ocean, land, desert, coastal, snow), so that the meteorology is also interpolated between times of ERBE observations. The CERES experiment expands the cloud conditions to include variations in optical depth, particle size, phase, and 3D geometry. Surface types are expanded to distinguish between several vegetation types (forest, grassland, savannah, etc.).

The ERBE time interpolation method was designed to provide accurate estimates of the monthly mean TOA flux. Many of the goals of CERES involve scientific objectives related to shorter timescales, such as the production of global synoptic maps. To reduce instantaneous errors in these products, an alternate approach to temporal interpolation involving narrowband data from geostationary satellites is also being investigated. While the limited spectral coverage of narrowband measurements (Doelling et al. 1990; Minnis et al. 1991) and the much lower absolute accuracy of shortwave narrowband calibration (Klein and Hartmann 1993) limit the accuracy of broadband fluxes inferred directly from narrowband data, these data do contain valuable information on the variations in meteorology occurring between the times of CERES observations. If the narrowband–broadband relationship is dynamically “calibrated” as a function of surface and atmospheric conditions by using time-coincident measurements from CERES, then narrowband geostationary data can be used successfully to provide time interpolation of broadband radiative flux data. Simulations have been performed that used geostationary data in the time interpolation of ERBE measurements, where the narrowband data are first converted to a simulated broadband flux estimate using the results of regional narrowband–
broadband correlations. Each flux estimate for a given time is then renormalized to the nearest ERBE broadband observation. These studies demonstrated that the instantaneous interpolation error can be reduced by 58% for LW flux and 46% for SW flux (Harrison et al. 1994). This enhanced geostationary data interpolation technique is currently being evaluated for CERES and will be important even for monthly average data whenever one or more of the three CERES satellite orbits is unavailable, as is expected for the period from the launch of TRMM in August 1997 until the launch of EOS-AM in June 1998 and EOS-PM in January 2000.

6. Synergism with other EOS instruments and interdisciplinary science investigations

While ERBE-like estimates of TOA fluxes are made using the CERES instrument alone, advances in estimating surface radiation budget and atmospheric radiative divergence require synergistic measurements from several EOS instruments. The instruments included for the first two EOS satellites and the TRMM spacecraft are given in Table 3.

Data from these instruments are used to derive the data products mentioned above, as well as to validate critical cloud and radiation parameter estimates. Remote sensing of clouds and radiation is analogous to unscrambling an egg composed of variable surface, atmosphere, and cloud properties, including the variable cloud and atmosphere vertical structure. Nonuniqueness of remote sensing solutions is a recurring problem. The critical advantage the EOS system has in attacking this problem is the multitude of independent physical processes that can be simultaneously observed for a given surface/atmosphere/cloud condition. These processes include radiance spectra from solar (MODIS, VIRS), thermal infrared [the Atmospheric Infrared Sounder (AIRS) MODIS, VIRS], and microwave [the Multifrequency Imaging Microwave Radiometer (MIMR), the Advanced Microwave Sounding Unit (AMSU), the TRMM Microwave Imager (TMI), Precipitation Radar (PR)] bands for the separation of scattering, absorption, and emission of radiation by the surface, atmospheric gases, and atmospheric particles. The processes also include polarization (MIMR, EOSP) and multiple-angle views [the Multiangle Imaging Spectroradiometer (MISR), CERES]. Instrument acronyms are defined in the appendix. Global cloud properties are derived from MODIS (TRMM instruments provide data only up to about 35° latitude); MIMR yields global cloud liquid water and precipitation information; AIRS/AMSU provide global temperature and water vapor profiles as well as high-spectral-resolution cloud emittance; and MISR data permit regional validation of bidirectional reflectance models, aerosols, and cloud height. The ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) provides the high spatial resolution (15 m) required to validate the effects of beam filling for broken cloud fields such as cumulus.

The synergistic use of these datasets can maximize the scientific utility of the CERES radiances measurements. Measurements from the cloud imager (MODIS) taken simultaneously with the CERES radiation budget measurements are especially critical to the success of the CERES experiment. Synergism of multiple spacecraft platforms is also required to properly sample the diurnal variation of radiation. Requirements are for two sun-synchronous platforms (one morning, one afternoon) plus one inclined orbit (varying time of day).

The above instruments are those required to measure the earth’s radiant energy system. For studies of the complete energy cycle, measurements of vertical and horizontal transfer of latent and sensible heat by the atmosphere and ocean are also required. Key measurements for these studies include the following.

- Precipitation: Active precipitation radar (PR) and passive microwave (TMI) measurements from TRMM; MIMR on EOS-PM; MIMR on the European Space Agency’s Meteorological Operational Satellite

- Temperature/humidity: AIRS, AMSU, MHS, and MIMR on EOS-PM

- Surface wind: Scatterometer on ADEOS-II (Advanced Earth Observing System II) (Japan)

- Ocean currents: Altimeter

7. Concluding remarks

The CERES experiment is designed not only to monitor changes in the earth’s radiant energy system and cloud systems, but to provide these data with suf-
TABLE 3. Instruments for EOS-AM, EOS-PM, and TRMM.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Instrument</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOS-AM</td>
<td>ASTER</td>
<td>Imaging radiometer—High-spatial-resolution images of land surface, water, ice, and clouds</td>
</tr>
<tr>
<td>(1998 launch)</td>
<td>CERES</td>
<td>Scanning radiometers—Top-of-atmosphere broadband radiation</td>
</tr>
<tr>
<td></td>
<td>MISR</td>
<td>Imaging spectrometer—Multiangle, high-resolution narrowband radiances for angular-reflectance functions</td>
</tr>
<tr>
<td></td>
<td>MODIS</td>
<td>Imaging spectrometer—High-resolution cloud cover and properties</td>
</tr>
<tr>
<td></td>
<td>MOPITT</td>
<td>Correlation spectrometer—CO and CH₄</td>
</tr>
<tr>
<td>AIRS/AMSU/MHS</td>
<td>Infrared sounder and two passive microwave radiometers—Atmospheric temperature profile, humidity profile, total precipitable water, skin surface temperature, and spectral infrared cloud properties</td>
<td></td>
</tr>
<tr>
<td>EOS-PM</td>
<td>CERES</td>
<td>Scanning radiometers—Top-of-atmosphere broadband radiation</td>
</tr>
<tr>
<td>(2000 launch)</td>
<td>MIMR</td>
<td>Microwave radiometer—Precipitation rate, cloud water, water vapor, sea surface temperature, ice, snow, and soil moisture</td>
</tr>
<tr>
<td></td>
<td>MODIS</td>
<td>Imaging spectrometer—High-resolution cloud cover and properties</td>
</tr>
<tr>
<td></td>
<td>CERES</td>
<td>Scanning radiometers—Top-of-atmosphere broadband radiation</td>
</tr>
<tr>
<td></td>
<td>LIS</td>
<td>Lightning sensor—Rate, position, and radiant energy of lightning flashes</td>
</tr>
<tr>
<td>TRMM</td>
<td>PR</td>
<td>Active microwave radar—Precipitation</td>
</tr>
<tr>
<td>(1997 launch)</td>
<td>TMI</td>
<td>Passive microwave—Same properties as MIMR</td>
</tr>
<tr>
<td></td>
<td>VIRS</td>
<td>Visible infrared scanner—Cloud cover and properties</td>
</tr>
</tbody>
</table>

Sufficient simultaneity and accuracy to examine the critical cloud/climate feedback mechanisms that may play a major role in determining future changes in the climate system. The CERES instruments continue the long-term measurement of the earth’s radiation budget and provide continuity with the ERBE and pre-ERBE measurements. Investigations using CERES data will also provide improved estimates of broadband SW and LW flux at the earth’s surface and within the atmospheric column. Cloud properties include measured areal coverage, cloud altitude, SW and LW optical depths, particle size, and particle phase. Large, systematic, diurnal variations of radiation and clouds will be resolved by analyzing data from three spacecraft. The combination of these data with global climate model studies will enhance our understanding of the dynamics of the interaction of clouds and radiation and the dynamics of the atmosphere, which are critical issues for understanding global change. The CERES radiation budget data are also planned for use in a wide range of other EOS interdisciplinary science investigations, including studies of ocean, land, biological, and atmospheric processes.

For readers interested in further information, additional details on CERES data analysis algorithms, data systems, and data products are available on the Internet (http://asd-www.larc.nasa.gov/ceres/docs.html). A more complete discussion of the EOS science plan for clouds and radiation is given in Wielicki et al. (1995).

Acknowledgments. The authors would like to thank the many individuals who have contributed to the CERES experiment: the science team, instrument team, working groups, and data management team. Also, the clarity of the paper was substantially improved as a result of comments from two anonymous reviewers.
Appendix: Instrument acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ADEOS</td>
<td>Advanced Earth Observing System</td>
</tr>
<tr>
<td>AIRS</td>
<td>Atmospheric Infrared Sounder</td>
</tr>
<tr>
<td>AMSU</td>
<td>Advanced Microwave Sounding Unit</td>
</tr>
<tr>
<td>ASTER</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer</td>
</tr>
<tr>
<td>CERES</td>
<td>Clouds and the Earth’s Radiant Energy System</td>
</tr>
<tr>
<td>EOS</td>
<td>Earth Observing System</td>
</tr>
<tr>
<td>EOSP</td>
<td>Earth Observing Scanning Polarimeter</td>
</tr>
<tr>
<td>EOS-AM</td>
<td>EOS platform with morning (1030 descending node) equatorial crossing time</td>
</tr>
<tr>
<td>EOS-PM</td>
<td>EOS platform with afternoon (1330 ascending node) equatorial crossing time</td>
</tr>
<tr>
<td>ISCCP</td>
<td>International Satellite Cloud Climatology Project</td>
</tr>
<tr>
<td>LIS</td>
<td>Lightning Imaging Sensor</td>
</tr>
<tr>
<td>MHS</td>
<td>Microwave Humidity Sounder</td>
</tr>
<tr>
<td>MIMR</td>
<td>Multifrequency Imaging Microwave Radiometer</td>
</tr>
<tr>
<td>MISR</td>
<td>Multiangle Imaging Spectroradiometer</td>
</tr>
<tr>
<td>MODIS</td>
<td>Moderate-Resolution Imaging Spectroradiometer</td>
</tr>
<tr>
<td>MOPITT</td>
<td>Measurements of Pollution in the Troposphere</td>
</tr>
<tr>
<td>PR</td>
<td>Precipitation Radar</td>
</tr>
<tr>
<td>TMI</td>
<td>TRMM Microwave Imager</td>
</tr>
<tr>
<td>TRMM</td>
<td>Tropical Rainfall Measuring Mission</td>
</tr>
<tr>
<td>VIRS</td>
<td>Visible Infrared Scanner</td>
</tr>
</tbody>
</table>

References


