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Earth Radiation Budget Experiment

Preliminary Seasonal Results

Bruce R. Barkstrom, Edwin F. Harrison, and Robert B. Lee, III
Atmospheric Sciences Division, NASA Langley Research Center, Hampton, Va.

ERBE Science Team
NASA Langley Research Center, Hampton, Va.

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During the past 4 years, instruments of the Earth Radiation Budget Experiment (ERBE) have been collecting data on two satellites. The first of these is the Earth Radiation Budget Satellite (ERBS). The second is the operational NOAA-9 satellite. In addition, ERBE has instruments on the operational NOAA-10. The NOAA-10 instruments have been collecting data for the last 2 years. The ERBE Science Team has recently completed validation of an initial sampling of these data. As a result, the ERBE Project will be placing these data in the archive at the National Space Science Data Center (NSSDC). The validation activity has involved intensive examination of data in 4 months during 1985 and 1986: April, July, and October 1985, and January 1986. This paper reports on the data being placed in the archive to acquaint the scientific community with their availability.

ERBE Data Acquisition and Processing

Each of the satellites carrying ERBE instruments carries a pair of instrument packages. The first package is a scanner instrument for obtaining radiances from pixels about 40 km in diameter near nadir [*Kopia*, 1986]. An ERBE scanner has three spectral channels: total (TOT), shortwave (SW), and longwave (LW). The second instrument package is a nonscanner for obtaining large-scale Earth fluxes and solar irradiance measurements [*Luther et al.*, 1986]. The nonscanner has four Earth-viewing channels and a solar monitor. Two of the four channels that observe the Earth see it from limb to limb. These channels are called wide field of view (WFOV). The other two Earth-viewing channels are medium field of view (MFOV). These see an area about 1000 km in diameter. Like the scanner, the nonscanner has a total channel and a shortwave channel. The TOT channel has minimal spectral sensitivity. The SW channel has a silica filter that transmits only solar wavelengths (0.2 μm to about 4.5 μm). By subtracting the shortwave (SW) flux from total (TOT) flux, we obtain the emitted or longwave (LW) flux. A reference blackbody and an integrating sphere, both in a vacuum chamber, were the instrument calibration sources on the ground. In flight, an internal blackbody, evacuated tungsten lamps, and observations of the Sun check the stability and precision of the instruments.

The ERBE data processing system performs three major tasks. First, the system converts the telemetry data to calibrated radiation measurements at the instruments. Second, the system relates the satellite measurements to the instantaneous energy loss per unit area at the top of the Earth's atmosphere (TOA). **Because the equations for the nonscanners resemble those for atmospheric profile inversion, the ERBE investigators have called this second process "inversion" [*Smith et al.*, 1986]. In doing the instantaneous inversion, the Earth is classified into geographic types (ocean, land, desert, snow, and coast) and cloud categories (clear, partly cloudy, mostly cloudy, and overcast). Nimbus-7 observations (*Taylor and Stowe* [1984] and *Suttles et al.* [1988]) provide the data for** cloud categorization. The algorithm for classification is a maximum likelihood estimator (MLE) developed by *Wielicki and Green* [1989]. Because the satellite radiometers see a given portion of the Earth from a single direction, the MLE chooses appropriate Angular Distribution Models (ADMs) to relate radiances to fluxes. Third, and finally, the processing system averages the observations over time [*Brooks et al.*, 1986]. The data used in building the ADMs also provide an empirical characterization of the dependence of albedo upon solar zenith angle. The data processing system uses this dependence in integrating over time for daily and monthly averages of SW flux. In the LW, another empirical model accounts for daytime solar heating and nighttime cooling of desert and land surfaces [*Brooks and Minnis*, 1984].

The ERBE data processing system produces several data products. Table 1 lists the products entering the archive at the NSSDC. Three products are likely to be of general scientific interest. The first of these is the solar irradiance product (S-2). This product contains measurements of the solar irradiance taken about every 2 weeks as part of the ERBE calibration monitoring. The second product of general interest is the ERBE Processed Archival Tape, or PAT (ERBE product S-8). The data processing system produces one PAT per day for each of the three pairs of ERBE instruments. These data are primarily from instantaneous scanner pixels and from nonscanner measurements. Both satellite altitude and top-of-the-atmosphere (TOA) fluxes are on this product. The third product of general interest is the Monthly Archival Tape (S-4), which contains time series of averages of TOA fluxes organized on a regional basis. There is one S-4 tape per month. In later sections of this paper, we will discuss data drawn from these three products.

ERBE Validation

During the past 4 years, the ERBE data have been subject to an intensive validation effort. There is no method of measuring the Earth's radiation budget that is independent of the satellite measurements. Thus intercomparisons between the various ERBE measurements are the primary source of validation information. The fact that ERBE has seven Earth-viewing channels on each of three satellites is a significant aid in this work. ERBE validation criteria include Consistency of Independent Checks of Sensor Calibration; Satellite Altitude Agreement of Scanner and Nonscanner on Each Satellite; Agreement of Instantaneous, Colocated Measurements on Several Satellites; Spectral Consistency of Three-Channel Scanner Observations From a Single Satellite; Agreement of Instantaneous TOA Fluxes Measured by the Scanner and by the Nonscanner; Satisfactory Checks of Limb Darkening and Bidirectional Models; Satisfactory Checks of Scene Identification; Satisfactory Checks of Time Averaging; Checks Against Other Sources of Data; and Reasonableness of Global, Annual Radiation.

Let us consider three examples of these results. First, the ERBE data have been carefully checked with the internal calibration sources carried on the instruments themselves. There is no evidence for systematic effects greater than 0.5% over 4 years.

Second, on any of the three satellites tne scanners see the same geography as the nonscanners. Observations of each instrument type are also nearly simultaneous. Thus two of the validation criteria have involved integrating scanner data to simulate the nonscanner observations. At satellite altitude the scanner measurements must be "turned" from sightings in the cross-track direction to the direction in which the nonscanner observed them. At TOA the scanner flux estimates must be integrated over the geographic area seen by the nonscanner. The results of these intercomparisons show that the two kinds of instruments have the same gain and are calibrated to the same radiometric scale to better than 1%. At satellite altitude the differences between the scanners and the nonscanners

Cover. Regional distribution of annual average clear-sky albedo based on April, July and October 1985 and January 1986. The distribution of the fraction of solar energy reflected from the top of the atmosphere for clear skies is shown. See "Earth Radiation Budget Experiment" by Bruce R. Barkstrom et al., page 297, this issue.

TABLE 1. ERBE Archival Data Products

Designation	Contents	Medium	Period
	Telemetry Archival Products		
S-1	raw radiometric counts, converted housekeeping, Earth located (RAT)	Tape	Daily
S-5	orbital ground track plots (archived in S-1 Monthly Product Summary)	Paper	Daily
	Product With Instantaneous Geophysical Observations		
S-2	solar irradiance from biweekly calibrations	Tape	Monthly
S-7	instantaneous nonscanner measurements inverted to the top of the atmosphere	Tape	Monthly
S-8	instantaneous scanner and nonscanner measurements inverted to the top of the atmosphere (PAT)	Tape	Daily
	Products With Instantaneous, Regional Averages		
S-9	regionally averaged scanner data	Tape	Monthly
S-10	regionally averaged nonscanner data	Tape	Monthly
	Products With Monthly Averages Only		
S-4	regional, zonal, and global averages of longwave, shortwave, and albedo at 2.5° and larger scales	Tape	Monthly

ERBE Science Team principal investigators:

B. R. Barkstrom, ERBE Experiment Scientist and Science Team Leader, Atmospheric Sciences Division, NASA Langley Research Center, Hampton, Va.; R. D. Cess, State University of New York at Stony Brook; J. A. Coakley, Jr., Oregon State University, Corvallis; Y. Fouquart, LOA, University of Lille, France; A. Gruber, NOAA National Environmental Satellite Data and Information Service, Washington, D.C.; D. L. Hartmann, University of Washington, Seattle; E. F. Harrison, NASA Langley Research Center, Hampton, Va.; F. B. House, Drexel University, Philadelphia, Pa.; R. S. Kandel, Laboratoire de Météorologie Dynamique,, Centre National de la Recherche Scientifique, Palaiseau, France; M. D. King, ERBE Project Scientist, NASA Goddard Space Flight Center, Greenbelt, Md.; A. T. Mecherikunnel, NASA Goddard Space Flight Center, Greenbelt, Md.; A. J. Miller, NOAA National Meteorological Center, Suitland, Md.; V. Ramanathan, University of Chicago, Ill.; E. Raschke, University of Koln, Federal Republic of Germany; G. L. Smith, NASA Langley Research Center, Hanpton, Va.; W. L. Smith, University of Wisconsin, Madison; and T. H. Vonder Haar, Colorado State University, Fort Collins. The article by Barkstrom entitled "The Earth Radiation Budget Experiment (ERBE)" (January 1984 *Bulletin of the American Meteorological Society*, pp. 1170–1185) lists the complete ERBE Science Team.

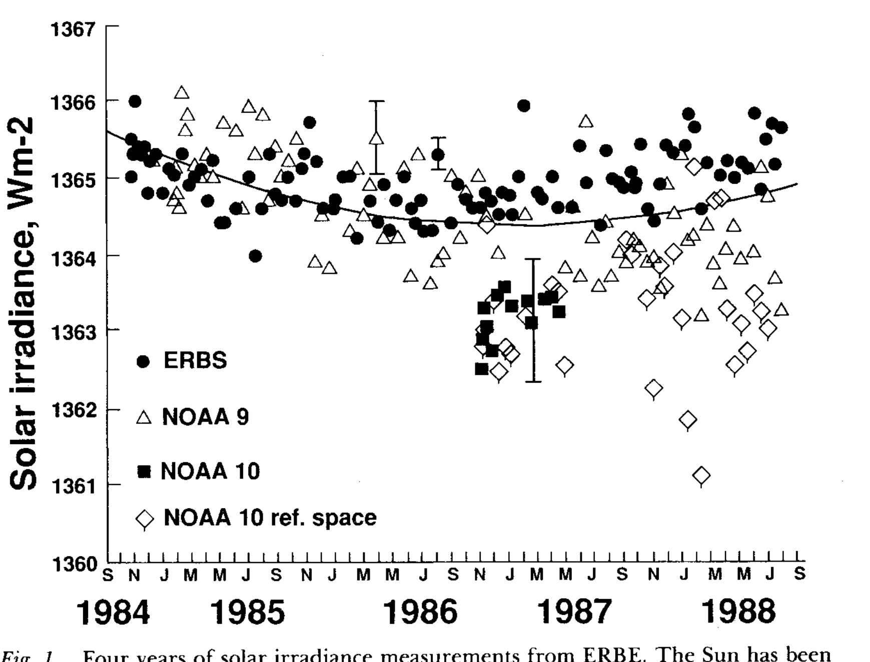

Fig. 1. Four years of solar irradiance measurements from ERBE. The Sun has been observed from all three of the satellites carrying ERBE instruments. The ERBE solar irradiance monitors are all Active Cavity Radiometers. The shutter on NOAA 10 failed after 6 months. Thereafter, space was used as a zero reference.

are about 2 W m^{-2} for the WFOV instruments and about 2 W m^{-2} for the MFOV.

Third, the time series from the ERBE interpolations have been compared with time series from the visible and infrared channels of the Geostationary Operational Environmental Satellite (GOES). The ERBE interpolations include the effects of the dependence of albedo on solar zenith. They also include the systematic time variations caused by solar heating of deserts and land during the day. The ERBE models provide a reasonable procedure for time interpolation. This conclusion is demonstrated by the fact that the average difference between the ERBE monthly average and the GOES is less than 5 W m^{-2} over the GOES region of observation.

Although the validation criteria are not a final error analysis for ERBE, they do provide useful preliminary estimates of uncertainties in various products. First, on an instantaneous observation of radiance, we expect uncertainties of about 1% for longwave observations of filtered radiance and 2–3% for shortwave. Second, on an instantaneous observation of 2.5° × 2.5° regions, the ERBS-/NOAA-9 intercomparisons offer reasonable estimates of uncertainty. These are ±5 W m^{-2} in the longwave, and±15 W m^{-2} in the shortwave. Third, on a monthly average, regional basis, the uncertainties are ±6 W m^{-2}, based primarily on the previously published estimates from GOES [*Harrison et al.,* 1983]. Fourth, the uncertainty in global, annual average net radiation is probably about ±5 W m^{-2}. This estimate is based on the imbalance from the 4 validation months. We will discuss this conclusion in a later section of this paper. A definitive error analysis is being actively pursued. However, such an analysis requires improvements in estimating the covariances of the radiation fields. The analysis also needs improved mathematical techniques for estimating uncertainties when the radiation fields are sampled irregularly and sparsely in time, space, and angle.

ERBE Solar Constant Observations

As we have already mentioned, ERBE carries a solar monitor on each of its three satellites [*Lee et al.,* 1987]. These data have been archived up to about 6 months before the data of this publication and are available from the NSSDC. Figure 1 shows the data from all three of the ERBE solar monitors over the first 3 years of observation. The mean value of the observations is about 1365 W m^{-2}. During the first 2 years, the solar irradiance was declining at a rate of about 0.03% per year. After solar sunspot minimum in 1986, the ERBE irradiance observations increased at a rate of about 0.02% per year [*Lee et al.,* 1989]. These trends are consistent with those of the Solar Maximum Mission [*Willson and Hudson,* 1988] and of Nimbus-7 [*Hickey et al.,* 1989]. In Figure 1 the 1988 NOAA 10 measurements exhibit a noticeably higher scatter than those for the 1986–1987 period. We used observations of the solar monitor's shutter every 32 s as the reference for zero irradiance during the earlier period. In April 1987 the shutter failed to close. Thereafter, we use observations of space about 10 min before and after the solar observations as the reference. As Figure 1 shows, the shuttered measurements are more precise and have less scatter than the space-referenced observations.

ERBE Earth-Viewing Results

The ERBE Science Team recognized that they could not intensively examine each pixel. There are about 1.5 million pixels for each day for each scanner channel. Thus we chose 4 months in 1985 and 1986 for detailed intercomparisons. To try to assure a reasonable coverage of the annual cycle, we chose 1 month from each season: April, July, and October 1985, and January 1986. We also placed high priority on 3 special data periods. First, November 1984 observations by ERBS provide data for radiative transfer intercomparisons. Second, along-track observations in January and August 1985 provide data for validation of ADMs. Third, during some special periods, ERBE could be coordinated with a validation period for the First International Satellite Cloud Climatology Project Regional Experiment (FIRE). After these data sets are archived, the team's strategy is to process the data to fill a complete, continuous 1-year period (April 1985 through March 1986). The data we discuss in the rest of this paper are taken from the 4 validation months. Mostly, we will discuss monthly averages produced by the ERBS and NOAA-9 together.

Monthly Average Results for July 1985

The ERBE monthly products are primarily reflected (SW) and emitted (LW) fluxes from 2.5° latitude × 2.5° longitude regions. Figure 2 shows the LW flux for July 1985. The Intertropical Convergence Zone (ITCZ) is clearly visible between 5° and 10° north. The cloud tops produce an average flux of about 200 W m^{-2} there. The clear areas immediately north and south have values near 300 W m^{-2}. The summer monsoon is also clearly visible over the Indian Ocean and the Indian subcontinent. The asymmetry in solar heating in July also causes the asymmetry of longwave radiation between the North Pole (about 200 W m^{-2}) and the South Pole (about 125 W m^{-2}).

Figure 3 shows the geographic distribution of average reflected flux for July 1985. The latitudinal structure in this figure reflects the typical conditions of solar illumination. The Sun is most nearly overhead near 20°N, with other latitudes having the Sun closer to the horizon, on average. Because the albedo of almost all surfaces increases as the Sun approaches the horizon, the monthly average albedo also increases away from the subsolar latitude. Thus the reflected flux is larger in the mid-latitudes and polar regions than it would be for a Lambertian surface. The longitudinal distribution of the reflected flux reflects the underlying geographic distribution of land and snow and the overlying traces of cloud presence and absence. For example, the ITCZ is particularly visible in the increase of reflected flux just north of the equator over the Eastern Pacific. The signature in the Western Tropical Atlantic is weaker, suggesting that advected cirrus from continental convection causes the strong ITCZ signature in the LW. In contrast, the Sahara is almost certainly a cloud-free area with a high underlying albedo.

Annual Average Clear-Sky Fluxes

The ERBE data processing system also produces measurements of clear-sky fluxes. The S-8 product contains these fluxes for the in-

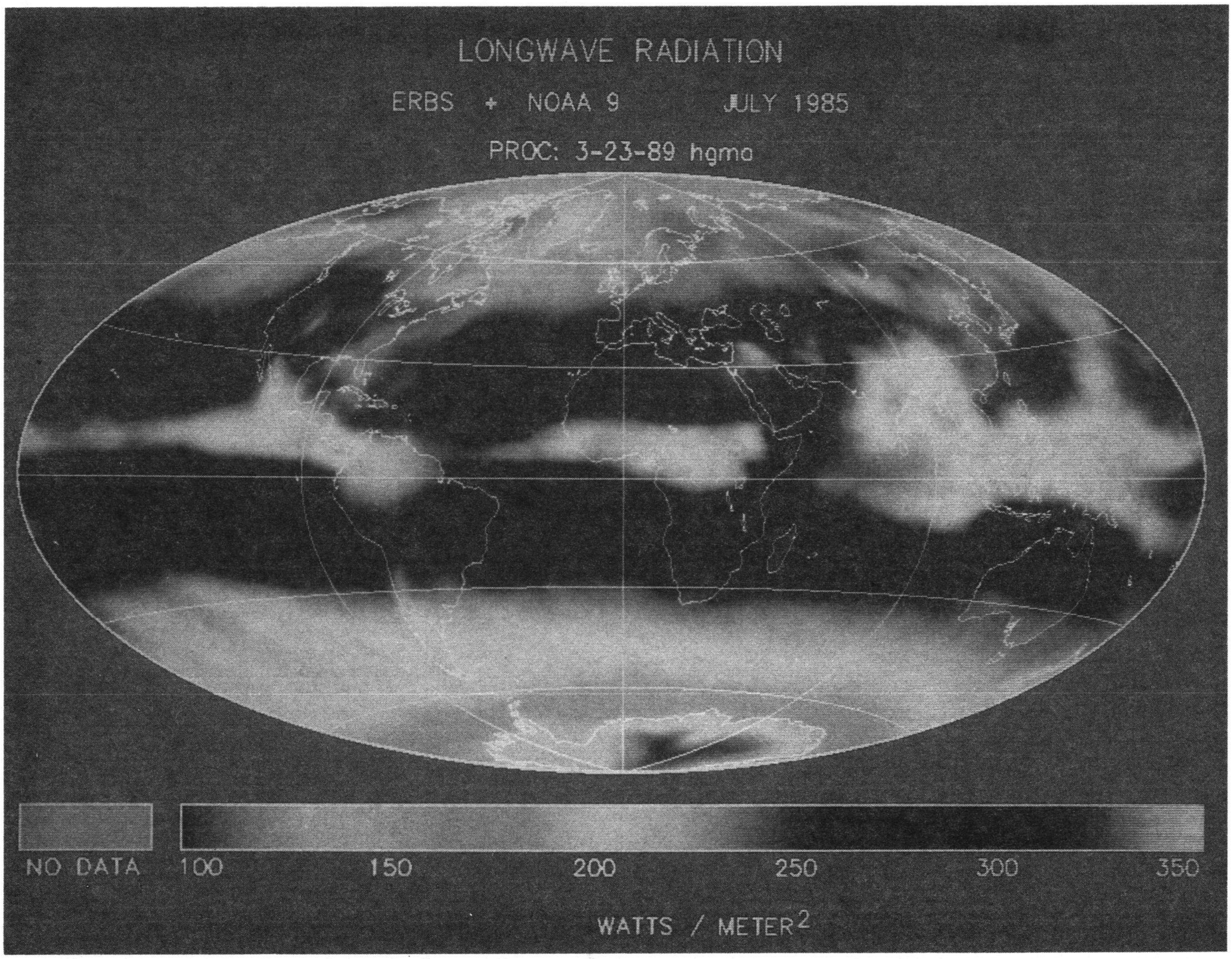

Fig. 2. Longwave fluxes for July 1985. The geographic distribution of LW flux averaged over that month are shown. This illustration originally appeared in full color. See the back of this volume for the color plate.

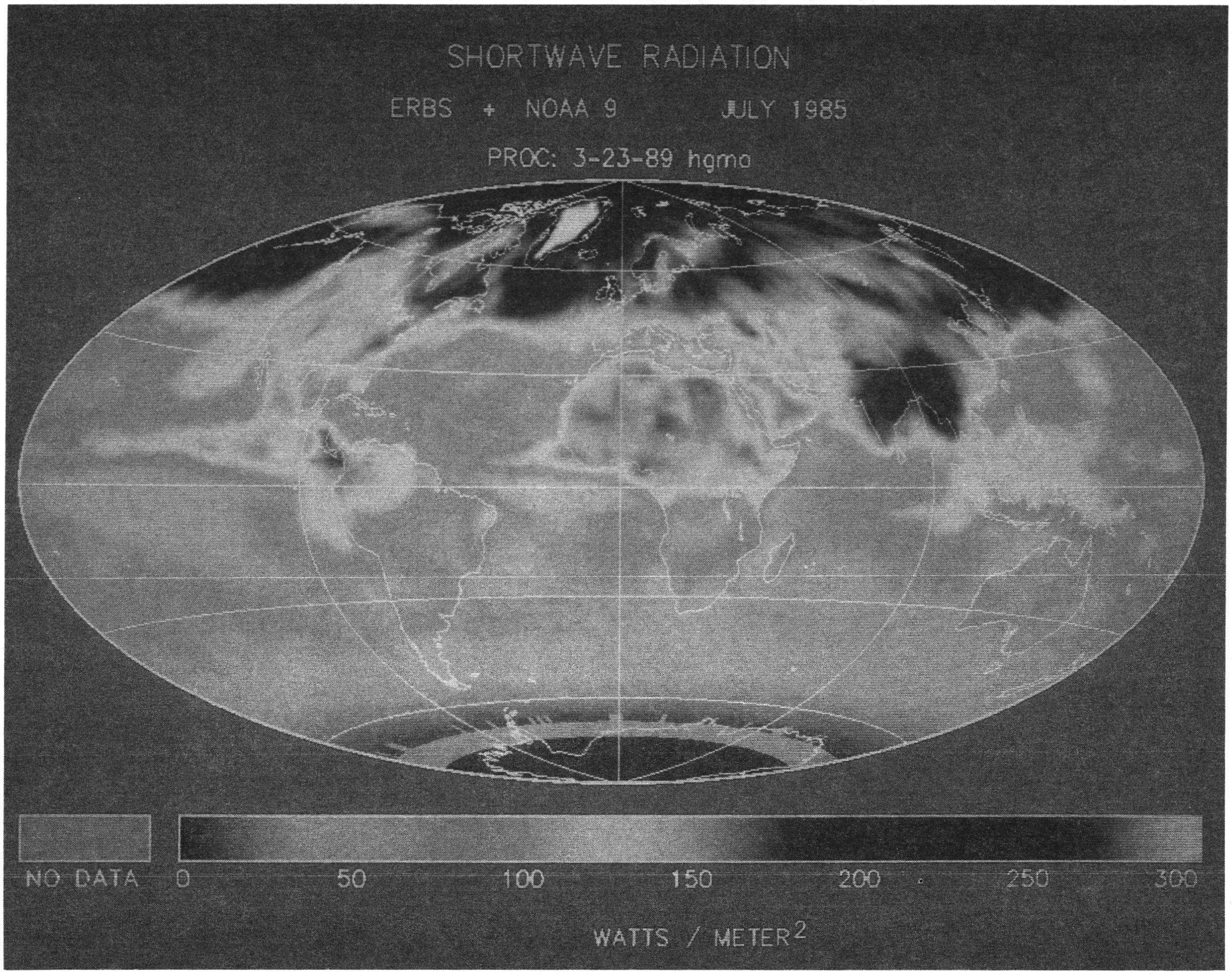

Fig. 3. Shortwave fluxes for July 1985. The geographic distribution of SW flux averaged over that month are shown. This illustration originally appeared in full color. See the back of this volume for the color plate.

stantaneous pixels that are identified as clear. The monthly averaged product, S-9, also contains monthly averaged clear-sky fluxes. The cover photo shows the annual average clear-sky albedo based on the data from the 4 validation months. Areas with no data had at least one month in which clear-sky observations were not seen or were not regarded as trustworthy.

The TOA albedo of oceanic areas is lowest where the Sun is most directly overhead. For annual average conditions, this is the tropics, which cover the latitude belt from about 22°N to 22°S. In this belt the albedo of clear skies is about 10%. The Sahara Desert is a major longitudinal perturbation in this belt. Overall, the TOA albedo over the Sahara is about 45%. For areas north or south of the high Sun, the albedo is larger. The clear-ocean albedo increases most rapidly. Near 45°N, this albedo approaches 15%. At the southern rim of the Pacific, it reaches values as high as 20%. The albedo of land areas also increases as the average position of the Sun is lower in the sky. However, the increase for land and desert is not as rapid as it is for the oceans. For example, North America and Europe have clear-sky albedos of 15-20%.

Although we do not discuss it here, the ability to separate clear sky fluxes from other conditions gives us the ability to investigate cloud radiative forcing. This quantity is an estimate of the effect of clouds on the Earth's radiation budget [e.g., *Ramanathan et al.*, 1989*a*, *b*.]

Annual Average, Zonal, and Global Results

Although only the 4 seasonal months used for validation have entered the archive, their fluxes may be used to estimate the first annual cycle of radiation from ERBE. Figure 4 shows zonal averages of LW flux for each of these 4 months. Figure 5 shows the SW fluxes.

The seasonal variations in LW flux reflect two major phenomena. The first is the summertime warming of the pole, followed by its wintertime cooling. The second major feature is the latitudinal wandering of the ITCZ. This feature appears in Figure 2 as the dip in the zonal average flux caused by the cirrus shields there. In July 1985, the ITCZ is close to the equator. In January 1986 this feature has moved to about 20°S.

The SW flux reflects similar meteorology. For this field the variation of solar irradiance dominates the zonal profiles. Although April and October 1985 are fairly symmetric, July 1985 and January 1986 are not. The Antarctic continent is much more reflective than the Arctic ocean. Thus the darker surface amplifies the 6% decrease in solar irradiance from January to July in producing the reflected radiation field.

Table 2 presents a summary of the global radiation fields for the 4 validation months and for the annual average that can be computed from them. The ERBE data will probably have an annual cycle of radiation that has an average albedo near 30%. The annual average LW flux will be near 235 W m^{-2}. With a mean solar irradiance of 1365 W m^{-2}, the ERBE measurements will be out of balance by about 6 W m^{-2}. We believe that the uncertainty in the global, annual average net radiation is about the same size.

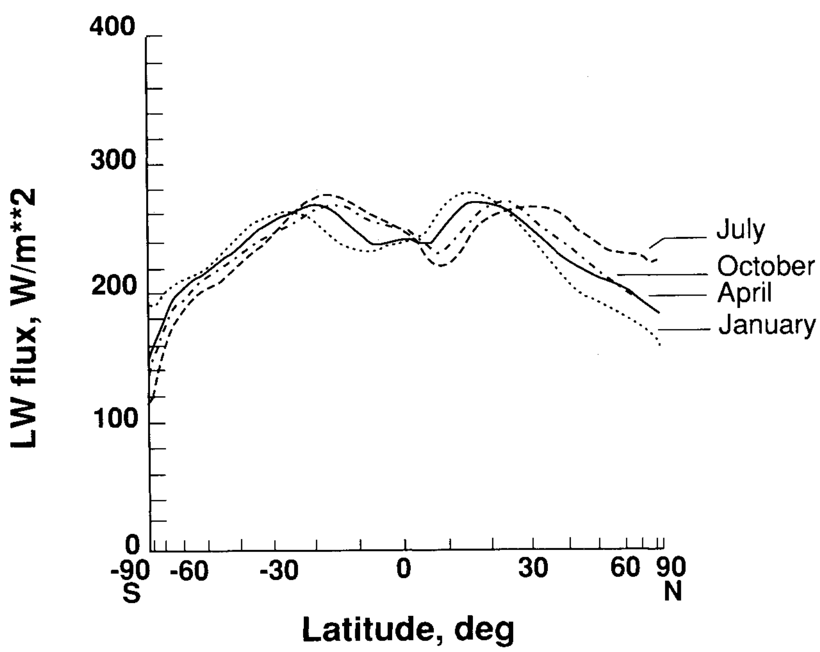

Fig. 4. Zonal average longwave flux for the 4 validation months. The months are April, July and October 1985 and January 1986.

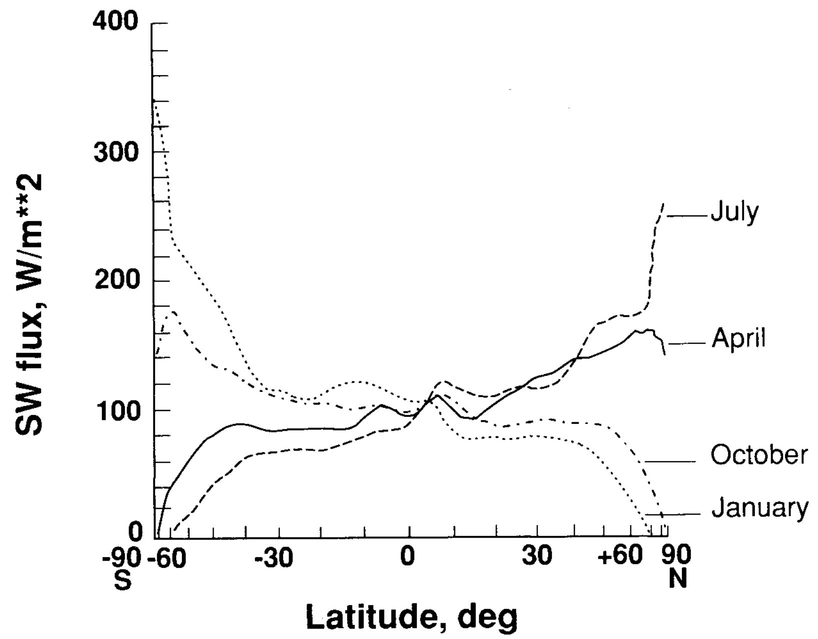

Fig. 5. Zonal average reflected flux for the 4 validation months. These are the same months as are shown in Figure 4.

TABLE 2. Global Radiation Fluxes From 4 Months of ERBE Observations

Month	Albedo, %	SW Flux, W m^{-2}	LW Flux, W m^{-2}	Net Flux, W m^{-2}
April 1985	29.7	101	234	5
July 1985	29.2	97	238	−1
October 1985	29.8	102	234	8
January 1986	30.9	109	232	13
Annual Mean	29.9	102	235	6

Figure 6 shows the energy transport constraint produced by the ERBE measurements. Briefly, the annual average of net radiation is positive near the equator and negative near the poles. Thus the atmosphere and the oceans must transport the energy excess away from the tropics. If we integrate the net radiation (absorbed solar flux minus emitted flux) from the North Pole to other latitudes, we arrive at the required energy transport. The solar irradiance contribution to this integral is computed from the ERBE solar irradiance measurements and the known geometry of the Earth. We compute the energy loss by reflection and emission from time averages of the measured fluxes, as we described in the section of this paper on the data processing system. For the values shown in Figure 6, we have removed the contribution to the net transport from the nonzero global average of the net radiation. Estimation of the net energy transport is one of the primary uses of the radiation budget measurements [e.g., *Bryan*, 1982; *Hartmann*, 1986; *Masuda*, 1988]. Figure 6 also shows estimates of this quantity by *Jacobowitz* [1979], by *Gruber* [1978], by *Ellis and Vonder Haar* [1976], and by *Vonder Haar and Ellis* [1974].

Hastenrath [1980, 1982] has commented on the relative uncertainty of the satellite altitude measurements. Although we have not completed a rigorous error analysis, we believe that the ERBE measurements should be of somewhat better quality than the previous estimates. There are several reasons why we believe this to be the case. First, the ERBE calibrations are almost certainly better than previous measurements, e.g., B. R. Barkstrom et al., unpublished manuscript, 1989. The scanners have not degraded significantly over the life of the mission. Second, ERBE has devoted much effort to improving the angular corrections needed to convert scanner radiances to fluxes. Previous measurements from the Nimbus 7 ERB provide most of the data for the ERBE models. Third, ERBE has included both solar zenith angle variations of albedo and systematic time variations in LW fluxes in the time-averaging process. Fourth, ERBE has used measurements from two satellites in providing the distribution of net radiation shown in Figure 6. The additional time sampling provided by the ERBS is particularly important in removing systematic errors caused by undersampling the time variations of flux [e.g., *Harrison et al.*, 1988]. The net transport shown in Figure 6 is higher than those previously shown by some of the earlier studies. They continue to support the suggestion that in situ oceanic estimates of heat transport are deficient by about 1-2 × 10^{15} W.

Conclusion

The ERBE data present a new level of accuracy in radiation budget measurements. The instruments are well calibrated and stable. The data processing system accounts for a number of important physical processes. These processes include angular distributions and the typical time dependence of the Earth's surface and the atmosphere above it. Furthermore, the use of cloud discrimination has provided a significant new source of information on the influence of clouds and the characteristics of clear-sky fluxes. This information is particularly important in under-

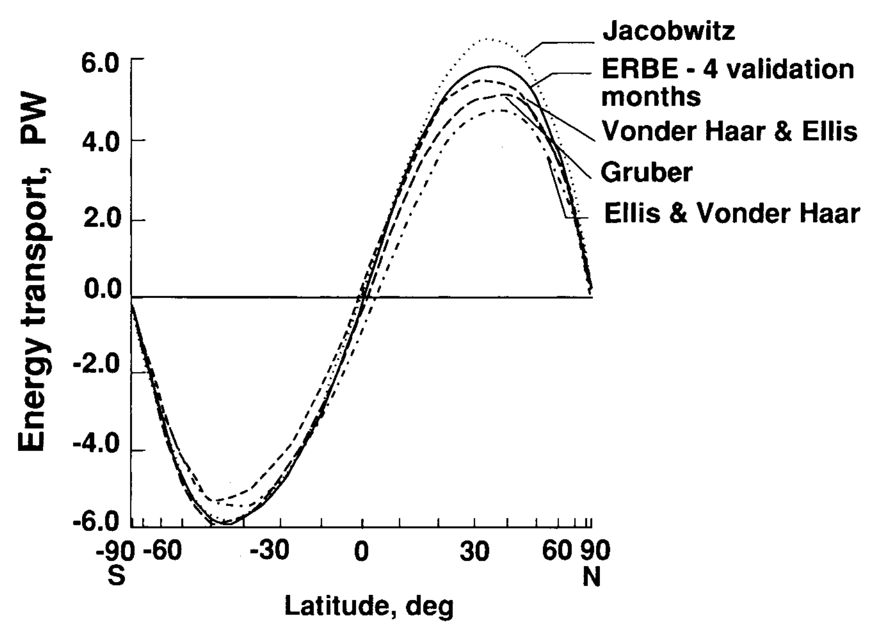

Fig. 6. Net energy transport constraint estimated from ERBE data for 4 validation months. For comparison, we also show satellite estimates from *Vonder Haar and Ellis* [1974], *Ellis and Vonder Haar* [1976], *Gruber* [1978], and *Jacobowitz et al.* [1979].

standing the current cloud forcing [e.g., *Ramanathan et al.*, 1989*a*, *b*; E. F. Harrison et al., unpublished manuscript, 1989]. It is also important in describing the response of clouds to climate change: the climate cloud sensitivity.

The ERBE data will be a major resource for the scientific community during the coming years. In the material presented here we have tried to illustrate the nature of the ERBE data and some of the interesting information that they contain. The data are available from the NSSDC. For requesters within the United States, the address is National Space Science Data Center, Code 633.4, Goddard Space Flight Center, Greenbelt, MD 20771; outside the U.S., use World Data Center A, Rockets and Satellites, Code 630.2, Goddard Space Flight Center, Greenbelt, MD 20771, USA.

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