Validation of a Technique for Estimating Outgoing Longwave Radiation from HIRS Radiance Observations

ROBERT G. ELLINGSON, HAI-TIEN LEE, AND DAVID YANUK

Cooperative Institute for Climate Studies, Department of Meteorology, University of Maryland, College Park, Maryland

ARNOLD GRUBER

NOAA/NESDIS, Washington, D.C.

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ABSTRACT

Simultaneous observations by the Earth Radiation Budget Experiment (ERBE) scanning radiometer and the High-Resolution Infrared Sounder (HIRS) on board the *NOAA-9* spacecraft have been used to validate a multispectral technique for estimating the outgoing longwave radiation (OLR) from the earth–atmosphere system. Results from approximately 100 000 collocated observations show that the HIRS technique provides instantaneous OLR estimates that agree with the ERBE observations just as well as different ERBE scanners agree with each other—about 5 W m^{-2} rms. Although there are differences between the HIRS and ERBE estimates that depend upon the scene type and time of day, the HIRS technique explained more than 99% of the variance of the ERBE observations for both day and night observations. The results suggest that the HIRS OLR technique is a suitable replacement for the Advanced Very High Resolution Radiometer technique now used by the National Oceanic and Atmospheric Administration for operational estimates of the OLR.

1. Introduction

The longest continuous series of outgoing longwave radiation (OLR) data have been obtained from 10-μm window radiance observations on the National Oceanic and Atmospheric Administration (NOAA) operational satellites. However, those data have not been universally accepted, because they are estimated from the radiance in but one narrow spectral region and because of the varied success of comparisons with directly measured data. Results from the Earth Radiation Budget Experiment (ERBE, Barkstrom 1984) will help interpret the data from the operational satellite system. However, a major problem exists because a follow-up experiment to ERBE is not planned until the late 1990s. Meanwhile, it will be necessary to provide OLR estimates from the operational satellite system.

A multispectral OLR estimation technique was developed and used by Raschke et al. (1973) with data from the Medium-Resolution Infrared Radiometer (MRIR) flown on *Nimbus-3*. However, this type of technique has not been exploited for use with operational data from the NOAA High-Resolution Infrared Sounder (HIRS). Since the radiance data measured by HIRS contains more information on atmospheric variables than the Advanced Very High Resolution Radiometer (AVHRR), it is a potentially better instrument for operational estimates of the OLR. Recently, Ellingson et al. (1989) presented results from radiation model calculations that show the HIRS will yield fluxes with smaller rms errors than the AVHRR.

The *NOAA-9* spacecraft carried the HIRS along with the instrument package for the ERBE, thereby offering the opportunity for comparing flux estimates from the two instruments. Such comparisons are important because of the continuing need for information on the earth radiation budget and the absence of an operational radiation budget satellite system. The purpose of this paper is to show the magnitude of the agreement between HIRS and ERBE OLR estimates for simultaneous observations of different scene types.

2. ERBE and HIRS OLR estimation techniques

In this paper we will compare the OLR as inferred from the ERBE scanner with that inferred from the HIRS. The details concerning the flux inference techniques may be found in Smith et al. (1986) for the ERBE and in Ellingson et al. (1989) for the HIRS. That information is summarized below for completeness and for assistance with interpreting the results.

The ERBE analysis classifies the surface of each scene viewed from space as either ocean, land, desert, snow,

Corresponding author address: Dr. R. G. Ellingson, Cooperative Institute for Climate Studies, University of Maryland, Department of Meteorology, 2213 Computer and Space Science Bldg., College Park, MD 20742-2425.

or mixed ocean and land by a priori reference to a geographic map. Radiance observations from the cross-track scanner are used to dynamically determine cloud presence by comparing the measured radiances with a priori statistics. The scenes are classified as either clear, partly cloudy, mostly cloudy, or overcast using the radiance data with a maximum likelihood estimation method developed by Wielicki and Green (1989).

The OLR from each scene is estimated as

$$\mathrm{OLR} = \pi L(m, \theta) N(\theta), \qquad (1)$$

where N is the longwave radiance, θ is the satellite zenith angle, and L is the so-called anisotropic factor. The scene identification number, m, corresponds to a particular surface type and the cloud cover category (e.g., m = 1—clear ocean; m = 2—partly cloudy ocean). The anisotropic factors are based on extensive analysis of *Nimbus-7* radiance observations from near-homogeneous scenes as reported by Suttles et al. (1989).

It should be noted that the actual instantaneous OLR from a given scene may be written in a form identical to that of Eq. (1) with $L(m, \theta)$ replaced by the actual anisotropic factor (i.e., the ratio of the actual flux to the flux estimated assuming isotropy of the radiance at angle θ). The actual anisotropic factor depends upon the instantaneous distributions of the radiative properties of the volume sensed by the ERBE instruments. However, the ERBE analysis assumes that L may be assigned a fixed value at a given angle for a particular scene type and latitude. This may lead to OLR errors of the order of a few percent in extreme cases when looking at individual scenes, but the analysis performed by Suttles et al. (1992) shows the errors to be smaller for monthly averages of time varying scenes.

The ERBE scanner has three spectral channels covering the 0.15–200-μm (total), the 0.2–4.5-μm (shortwave), and the 6–35-μm (longwave) regions. All three channels are used in the analysis, but the OLR is primarily determined with the radiance obtained from the difference between the total and shortwave channels. During daylight, the cloud identification algorithm uses both the long- and shortwave observations. At night, cloud identification is accomplished with a threshold technique.

The ERBE analysis employs a variety of checks on the data, including on-board calibration in the longwave, extensive comparisons between the different scanning and nonscanning instruments, and inter-ERBE instrument checks. As such, the data produced by ERBE represent the best estimate of the top of the atmosphere radiation budget heretofore. A measure of the quality and consistency of the OLR data is the 5 W m^{-2} rms difference obtained from near-instantaneous intercomparisons of fluxes from the same scenes viewed by different ERBE scanners as reported by Barkstrom et al. (1989).

The OLR is estimated from the HIRS as the weighted sum of radiance observations in four narrow spectral intervals, given as

$$\mathrm{OLR} = a_0 + \sum_{i=1}^{4} a_i(\theta) N_i(\theta), \qquad (2)$$

where the a's are regression coefficients, and N is the observed radiance in the ith interval at angle θ.

The spectral intervals and the regression coefficients were determined with a stepwise regression analysis of calculations from a modified version of the radiation model of Ellingson and Serafino (1984) using 1600 soundings from Phillips et al. (1988) as input data. The surface and air temperatures were assumed equal, and a thin plate cloud was added randomly in the vertical to each sounding. Radiance and flux calculations were performed for completely clear and overcast conditions for each sounding, and the regression analysis was performed using all 3200 calculations in the sample.

The HIRS channels selected by the regression are

channel 7: 13.1–13.6 μm,
channel 10: 7.9–8.5 μm,
channel 12: 6.6–6.9 μm, and
channel 3: 14.3–14.7 μm.

A discussion of the physical significance of the various channels is given in Ellingson et al. (1989). The coefficients used in the analysis may be obtained from the authors electronically by mail (bobe@atmos.umd.edu) or ftp.

The regression analysis showed that the calculated OLR could be estimated to better than 1.5 W m^{-2} rms from the radiance in but four narrow spectral intervals. A particularly nice feature of the regression technique is the independence from surface and scene types. Additionally, if the clear-column radiances are also determined, as is done by the cloud-clearing procedures used in sounding applications with the HIRS data, the cloud forcing may be easily estimated. The clear-column radiances are also useful for relating changes in the outgoing flux to changes in the radiative properties of the atmosphere. However, the analyses presented herein use observed, not cloud-cleared, radiances.

Two modifications have been made to the model since the publication of our original results. One modification includes the use of the Malkmus (1967), rather than the exponential, distribution of line intensities with the Goody (1952) random band model. That modification was made following the results of Intercomparison of Radiation Codes in Climate Models (ICRCCM) (Ellingson et al. 1991), which showed better agreement between line-by-line calculations and narrowband models using the Malkmus model as compared to the Goody model with the same spectral line data. For clear sky conditions, the modified model yields OLR calculations that average about 4 W m^{-2} higher than the original calculations.

The second modification involves the treatment of cirrus clouds. Our initial analysis of ERBE data for overcast conditions (see below) showed the HIRS technique to overestimate the OLR relative to ERBE at OLR values less than 150 W m^{-2}. There was also a large angular dependence of the HIRS–ERBE differences for those low values. An examination of the model calculations showed that the lowest OLR value used in the regression analysis was about 150 W m^{-2}, whereas the observations reached as low as 90 W m^{-2}, particularly at high latitudes. However, the soundings used in the calculations extended only to 60°N. In other words, the regression model was being extended beyond the limits to which it had been fit.

Following the work of Haurwitz and Kuhn (1974), the original treatment of cirrus assumed a flux emissivity of 0.2 between 520 and 1360 cm^{-1}, and 0.5 elsewhere. Since the diffusivity approximation is used in the calculations, the cirrus optical depth was about 0.13 from 520 to 1360, and 0.42 elsewhere. The cirrus optical depth depends, of course, on the ice water content, the crystal habits, and the size distribution, each of which change from cloud to cloud. We discovered that increasing the optical depth in the 520–1360-cm^{-1} region by a factor of between 1.5 and 2.0 resulted in better agreement between the ERBE and HIRS nighttime fluxes below 150 W m^{-2}, both in absolute value and in angular dependence. Furthermore, those changes do not significantly change the agreement at other flux levels, as is shown below.

Except where noted otherwise, the results presented herein are based on a regression analysis of a set of 3200 model calculations using procedures and sounding data identical to those discussed in Ellingson et al. (1989). The radiation calculations used in the analysis have been modified by the use of the Malkmus (1967) transmittance model and by a different cirrus parameterization. The new cirrus parameterization follows the work of Haurwitz and Kuhn (1974) for all but the 520–1360-cm^{-1} region, where the cirrus optical depth

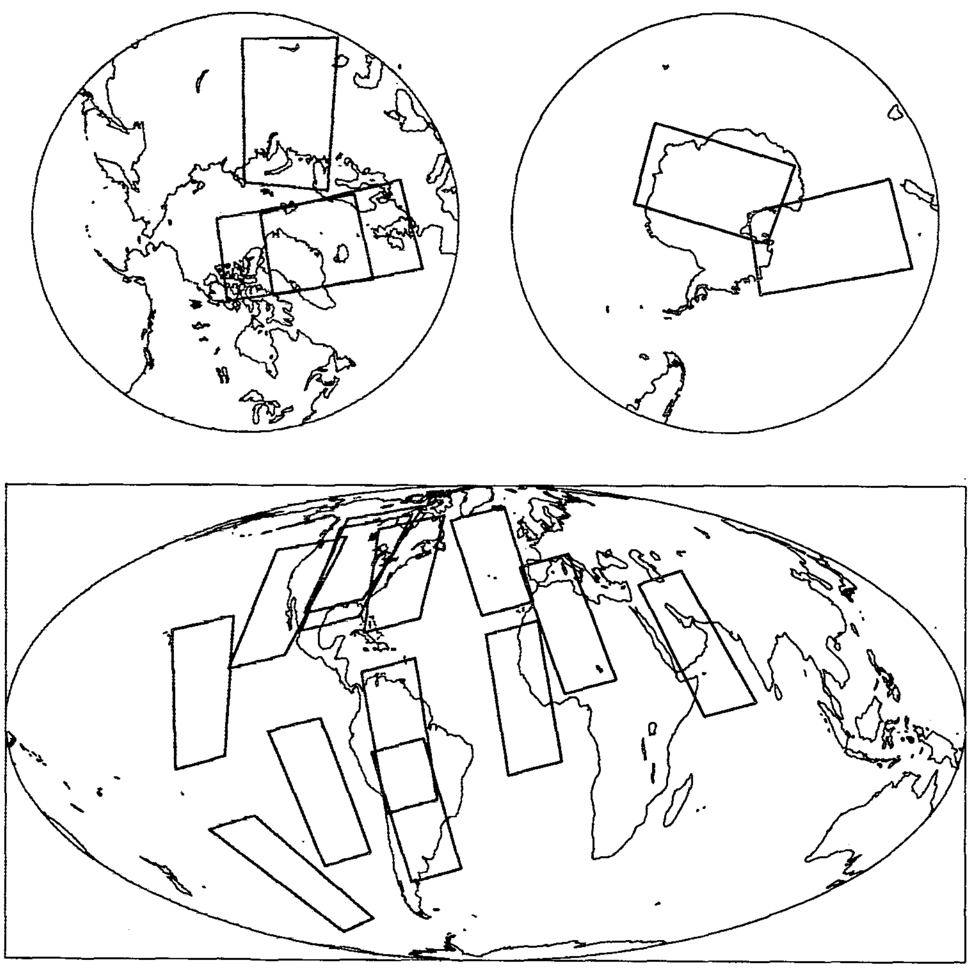

FIG. 1. Geographical distribution of scenes used in the HIRS–ERBE analysis.

has been increased by a factor of 1.75 (to a value of about 0.23). Although the modification of the cirrus emissivity is tantamount to tuning the inference scheme, we believe the selection is justified because of the lack of data for cirrus clouds, the lack of soundings for high latitudes, and the lack of sensitivity of the results at other flux levels.

3. Selection of data

The use of ERBE scanner data to validate the HIRS technique is complicated by the differences in the viewing and scanning properties of the HIRS and ERBE instruments. The ERBE scanner has a field of view at nadir of about 30-km diameter, whereas that for the HIRS is about 17 km. Furthermore, the ERBE scenes abut one another, whereas the HIRS scenes are separated by about 42 km at nadir.

Since the two instruments do not view identical scenes, we have attempted to design the analysis to select scenes for which the flux field is relatively homogeneous in the horizontal. The data have been processed in the following fashion. First, three consecutive ERBE scan lines were searched to find 3 × 3 arrays with identical scene identifications within the HIRS viewed area (±49° satellite viewing angle). If the standard deviation of the fluxes in the array was less than 2% of the mean flux from the array, the field was judged to be homogeneous. The HIRS data were searched to find all scenes that fell within the nine ERBE scenes. If there were two or more HIRS observations and if they met the same 2% homogeneity test relative to the HIRS flux estimate, the data were classified as collocated, and the array-averaged HIRS and ERBE data were selected for comparison. The ERBE scene identification information, m in Eq. (1), was determined by the ERBE data processing procedures as described

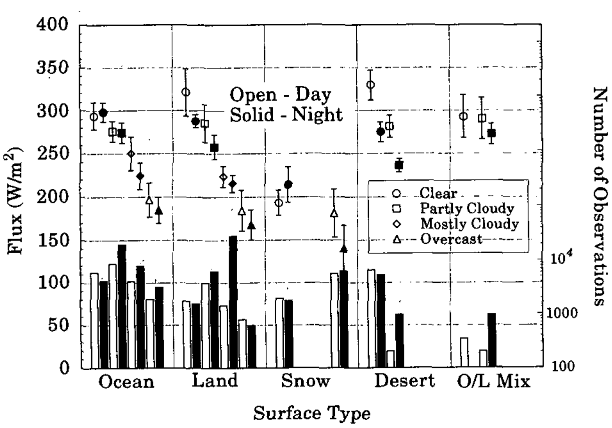

FIG. 2. Scene-dependent distributions of the number of observations (bars), the mean ERBE fluxes (symbols), and the standard deviations of the observations (vertical lines) obtained from the analysis.

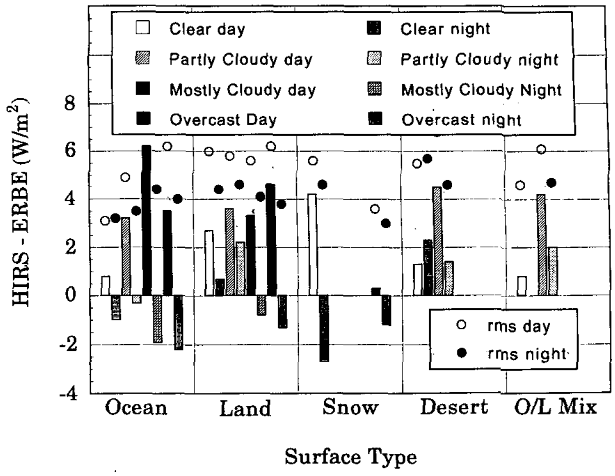

FIG. 3. Mean (bars) and rms (circles) HIRS–ERBE OLR differences for day and night observations of different surface and cloud scenes.

by Barkstrom (1984), Smith et al. (1986), and Wielicki and Green (1989).

It should be noted that a 49° satellite viewing angle corresponds to a local (scene) zenith angle of approximately 60°. Furthermore, the 2% homogeneity criteria was chosen to increase the number of samples in the partly cloudy and cloudy categories for some surface types. However, with the exception of the number of observations, a repeat of the analysis with a 1% flux homogeneity criterion does not significantly change the results obtained with the 2% test.

Homogeneous scene results were obtained for all scene types from 18 different regions (Fig. 1) for a period of six days and nights from the December 1987 release of the April 1985 ERBE/V5 tapes. These particular regions were identified by the ERBE science team for special attention because they cover a wide range of surface and cloud types. Our initial analysis divided the data according to the local time of the satellite equator crossing, that is, about 0130 and 1330. However, portions of the Northern Hemisphere were illuminated by the sun during each satellite overflight, whereas part of the Southern Hemisphere was always dark. The results shown here have been sorted by day and night conditions for the same equatorial crossing. Figure 2 presents some statistics on the selected ERBE fluxes as a function of surface and cloud conditions. Overall, we found about 42 000 and 57 000 collocated daylight and nighttime observations, respectively. Although data were obtained for all scene types, we do not show results from scenes with fewer than 200 observations.

4. Results and discussion

The differences between the HIRS and ERBE OLR estimates are summarized in Fig. 3 for different scenes and for night and day conditions. Figures 4 and 5 present summary statistics on the agreement between HIRS and ERBE for all scenes for day and night observations, respectively.

At night, there is little bias in the mean between the HIRS and ERBE fluxes, although the HIRS–ERBE regression line tends to slightly overestimate ERBE at high flux values and underestimate at low values. Nevertheless, the rms HIRS–ERBE differences are of the order of 4 W m^{-2} for all surface and cloud types. This is the same order of agreement of simultaneous measurements of identical regions by different ERBE scanners as stated by Barkstrom et al. (1989). However, the average flux differences show a dependence on the value of the flux, the surface type, and the cloud amount. For ocean and land surfaces, the HIRS–ERBE differences tend to become more positive when progressing from clear to partly cloudy conditions, and then more negative from partly to mostly cloudy to overcast conditions. Overall, the mean differences are within ±3 W m^{-2} for all scene types.

For daylight conditions, the HIRS technique overestimates ERBE by about 2.6 W m^{-2} on average for all flux values, and there is no flux dependence of the bias when all data are considered. However, the average and rms flux differences show a marked variation with cloud coverage for all surface types. For the same scene identification, the average difference between the HIRS and ERBE fluxes is more positive for day than for night conditions, except for the clear desert scene. With the exceptions of clear ocean and desert regions, the rms differences for the daylight scenes are greater than those for the corresponding night scenes. Nevertheless, the rms difference for the ensemble is but 5 W m^{-2} and the explained variance is about the same as for night data, 0.994.

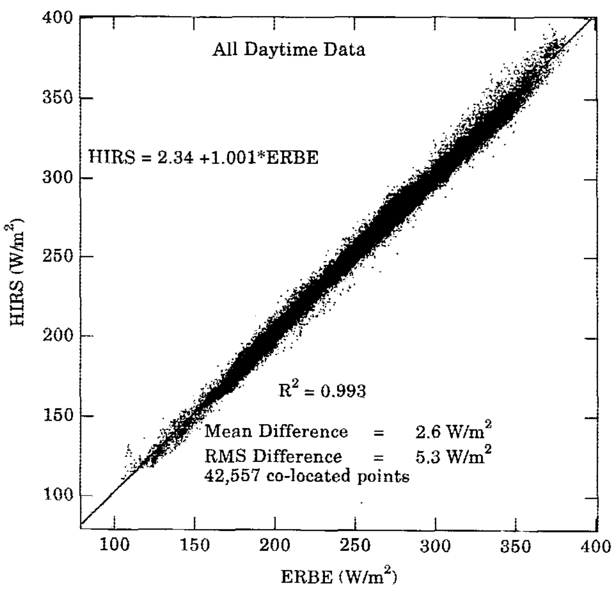

FIG. 4. Scatter diagram of HIRS and ERBE OLR estimates for daytime observations of all scenes. The straight line is a least-squares fit of the data, and the coefficients are given on the chart.

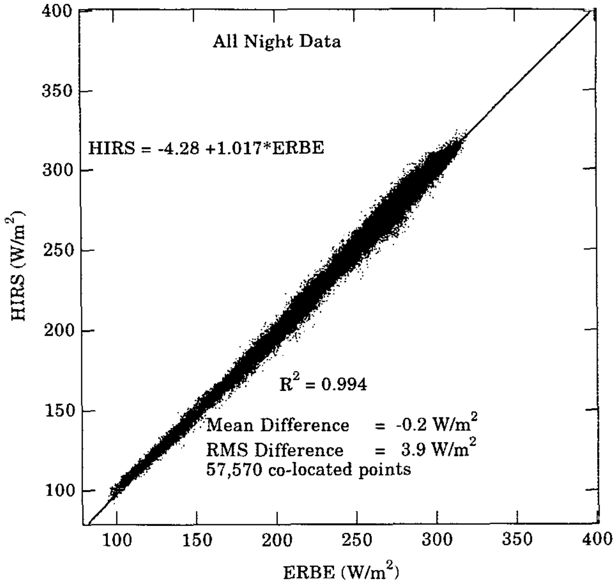

FIG. 5. As in Fig. 4 but for nighttime observations.

The actual reasons for the differences between the HIRS and ERBE flux estimates are difficult to ascertain because of the lack of detailed information concerning various scenes viewed by the instruments. Similarly, the day-to-night differences are difficult to interpret because we are not comparing results from exactly the same scenes. Nevertheless, we have attempted to explain some of the differences by examining uncertainties associated with regression analysis, the radiation model on which the regression scheme is based, and HIRS–ERBE observations. Errors in the radiation model are difficult to estimate because of the lack of an absolute standard for comparison with model calculations. However, our comparisons with the line-by-line calculations performed for the ICRCCM (Ellingson et al. 1991) showed differences of less than 2 W m^{-2} for the top of the atmosphere clear-sky flux calculations, with the model used for the regression analysis.

As noted above, perhaps the largest uncertainties for the model calculations are associated with overcast cirrus conditions for which we used a parameterization based in part on the nighttime ERBE data. Figures 6 and 7 illustrate the effects of the choice of cirrus optical depth on overcast and clear conditions, respectively. A 45° line is shown in each figure to aide in the interpretation. Note that as the cirrus optical depth used in the regression is increased, the major changes to the HIRS fluxes occur primarily at values less than 150 W m^{-2}. It appears as if the channels selected by the regression have a built-in cirrus detection capability.

The effect of the cirrus optical depth on the angular distribution of HIRS–ERBE differences is illustrated

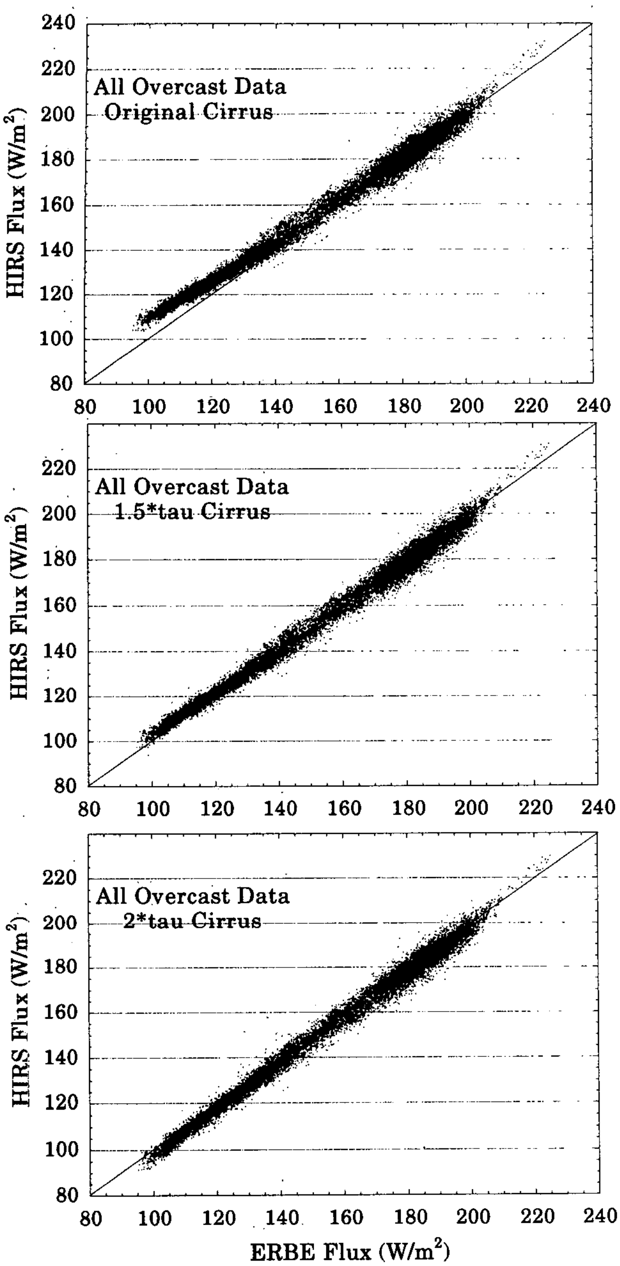

FIG. 6. Comparisons of HIRS with ERBE OLR estimates for nighttime overcast scenes when different cirrus parameterizations are used in the radiation model calculations. The 45° line is shown to illustrate the magnitude of the disagreement for different flux values.

in Fig. 8. With the original parameterization, the HIRS technique showed too little limb darkening relative to ERBE. The limb darkening increases as the cirrus optical depth increases. As the cirrus multiplier is increased from 1.5 to 2, the HIRS technique goes from having too little to too much limb darkening relative to ERBE. Our choice of 1.75 for the multiplier of the original cirrus optical depth yields almost the same limb darkening as ERBE and provides a better rms fit for the overcast conditions than either 1.5 or 2.0. The results for the daytime overcast snow conditions are very similar, although the bias noted above is apparent.

There are several potential causes for the differences between the mean and rms errors from day to night. First, for daylight conditions, the longwave flux is determined from the radiance resulting from the difference between the total and shortwave channels. Our calculations are for the wavelength range greater than 3.3 μm, whereas the ERBE fluxes are for wavelengths greater than 4 μm. This would have little effect for

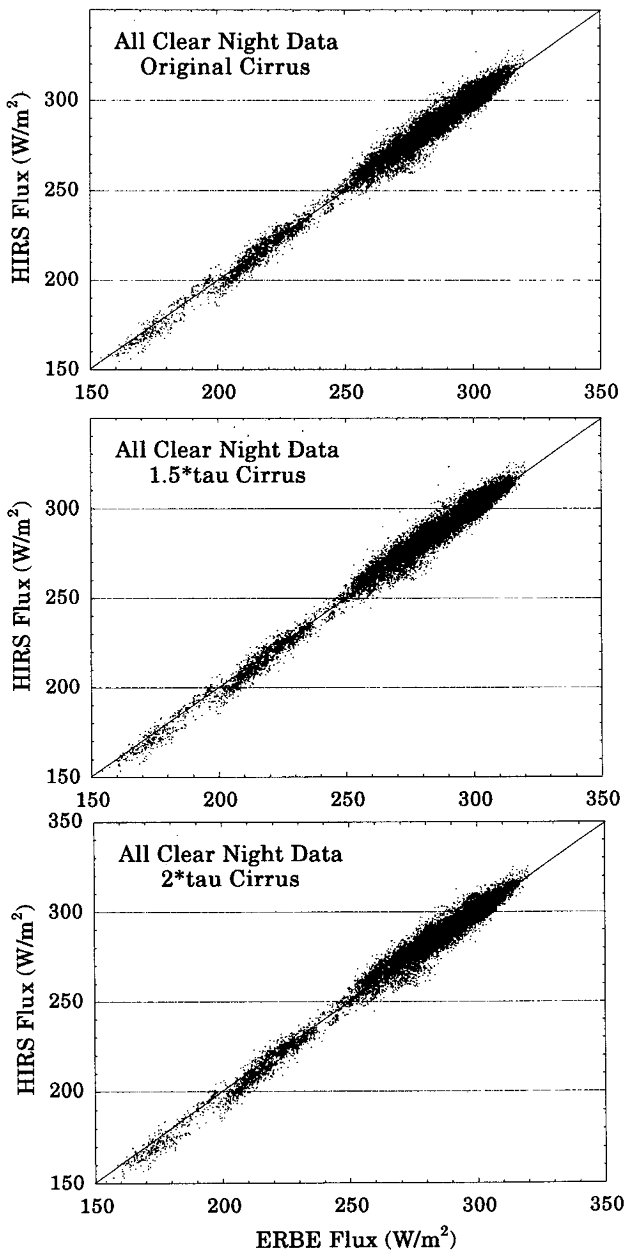

FIG. 7. As in Fig. 6 but for all clear cases.

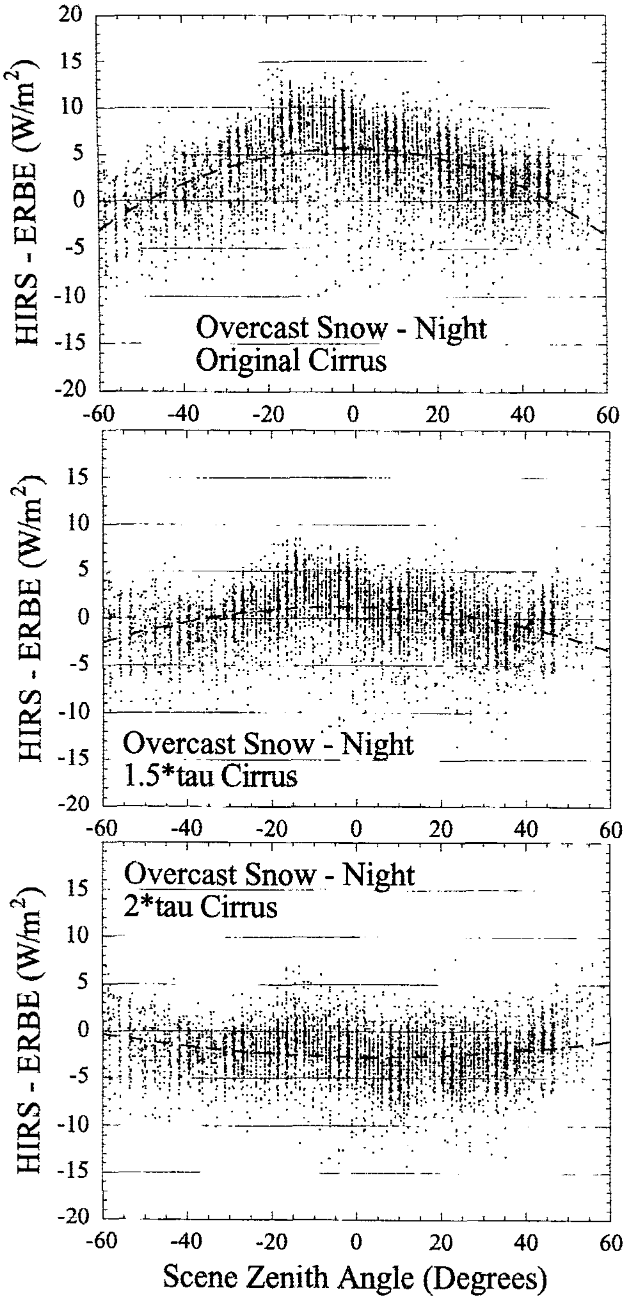

FIG. 8. Angular distributions of the HIRS–ERBE OLR differences for nighttime overcast snow scenes when different cirrus parameterizations are used in the radiation model calculations. The dashed lines represent least-squares parabolas fit to the data.

overcast conditions, but it would amount to about 1.7 W m^{-2} for warm, dry regions. This could account for about 50% of the differences seen over clear ocean regions, however.

Another possibility for day-to-night differences is error in the ERBE shortwave (SW) radiance–flux correction. If too much SW flux were subtracted, the longwave ERBE flux would be too small. Green et al. (1989) present some evidence that the *NOAA-9* SW scanner reads too high, but it is not clear whether this is an offset or a gain problem. Our results would be consistent with a gain problem, since it appears as if the daytime HIRS–ERBE differences depend on the albedo of the underlying surface (with the exception of desert regions). The effect of this on the OLR was studied by Gruber et al. (1990), who compared *NOAA-9* ERBE scanner measurements with Earth Radiation Budget Satellite (ERBS) scanner measurements (the ERBS did not suffer from biased SW measurements). We plan to investigate this in more detail in our analysis of this and additional time periods.

Another possibility for the day-to-night differences is a shift in the HIRS calibration between day and night. This seems less likely because such a shift would affect all scenes in a similar fashion.

The angular distributions of the HIRS–ERBE differences give added insight into possible causes for the

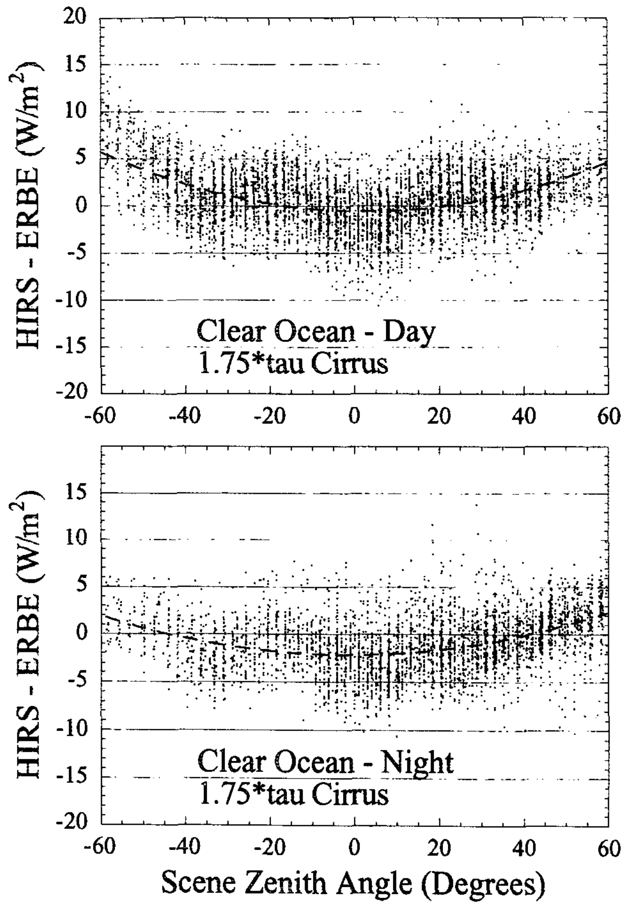

FIG. 9. Angular distributions of the HIRS–ERBE OLR differences for day and night clear ocean scenes. The sign of the angle depends on whether one is looking to the right (positive) or left (negative) of the orbital track. The dashed lines represent least-squares parabolas fit to the data.

differences. For ocean regions (Fig. 9), the HIRS technique shows more limb darkening than ERBE for both day and night. This is consistent with the Smith et al. (1989) analysis of ERBE along-track scans, which concluded that the anisotropic factors used by the ERBE processing do not have enough limb darkening, particularly those for clear through mostly cloudy scenes. That analysis indicated that for clear conditions, the ERBE fluxes are too high by about 2% at 0°, too low by about 2% at 70°, and about right at 55°. Our least-squares-fitted differences are about half as large as those estimated by Smith's analysis, and there is a near systematic shift in the fitted curve from day to night.

The ERBE analysis uses the same limb correction factors for both day and night observations, and this may be the cause for the day-to-night variations of the HIRS–ERBE differences over land and desert surfaces. Considerable differences in limb darkening over land and desert regions may occur from day to night, because, unlike oceanic regions, the temperature profile near the surface undergoes considerable change. Less limb darkening would be expected at night when temperature inversions form. Our analyses of the angular distributions of the HIRS–ERBE differences for desert (Fig. 10) and land (Fig. 11) support this hypothesis, particularly for desert regions. The day–night average limb model used in the ERBE analysis might be providing too little limb darkening during the day and too much at night for the land and desert surface types. This effect could overshadow the solar correction effect, particularly over the deserts.

An alternative hypothesis is that the regression analysis is in error, because it does not account for the nonblack surfaces or strong near-surface temperature gradients common to desert and land scenes. We tested the sensitivity of the regression technique to surface–air temperature discontinuities for different desert temperature profiles, and found that the regression technique agreed with our model calculations to within 1 W m^{-2} for a ±20°C range of temperature discontinuity. This is particularly gratifying since discontinuities were not included in the calculations used to derive the regression equation. These calculations will be detailed in a future journal article.

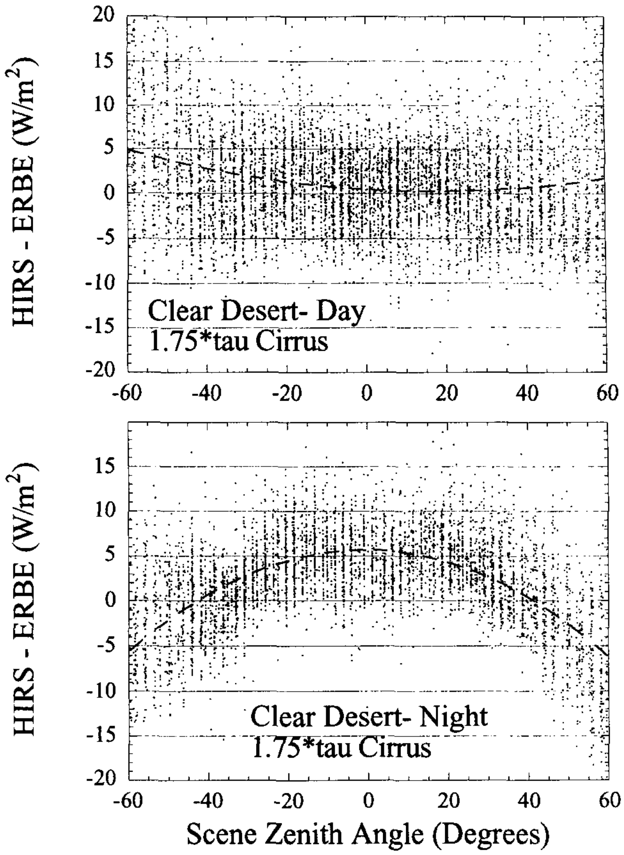

FIG. 10. As in Fig. 9 but for clear desert scenes.

5. Conclusions

Overall, the HIRS technique provides instantaneous flux estimates that agree with ERBE observations just as well as different ERBE scanners agree with each other—about 5 W m^{-2} rms. There are differences between the HIRS and ERBE estimates as regards angular distributions, the effects of different surface and cloud types, and day-to-night observations. Nevertheless, for the ensemble, the HIRS explained more than 99% of the variance of the ERBE observations for both day and night observations.

The HIRS–ERBE differences may be explained in part by known deficiencies in the ERBE analysis, by possible errors in the calibration of the *NOAA-9* shortwave scanner, and by deficiencies in the radiation model used to develop the HIRS technique, particularly the parameterization of cirrus clouds. For operational purposes, the uncertainties associated with daylight observations, be it with *NOAA-9* HIRS or ERBE, cause the greatest concern, particularly as regards estimates of the diurnal range of fluxes from different surface types. It may be possible to clarify these effects by examining the albedo dependence of the flux differences and/or by performing a similar analysis of data from *NOAA-10*, which also carried ERBE and HIRS instruments. Likewise, the cirrus parameterization may be found not to hold for other seasons. This possibility may be checked, however, with additional analysis of data from *NOAA-9* and *NOAA-10*.

The results of the HIRS–ERBE intercomparisons are encouraging as to the quality of the radiation model and the validity of the HIRS flux estimation technique. Overall, the results suggest that the HIRS technique is a suitable replacement for the AVHRR technique now used in NOAA operations, because it is not prone to the large systematic errors of the AVHRR technique

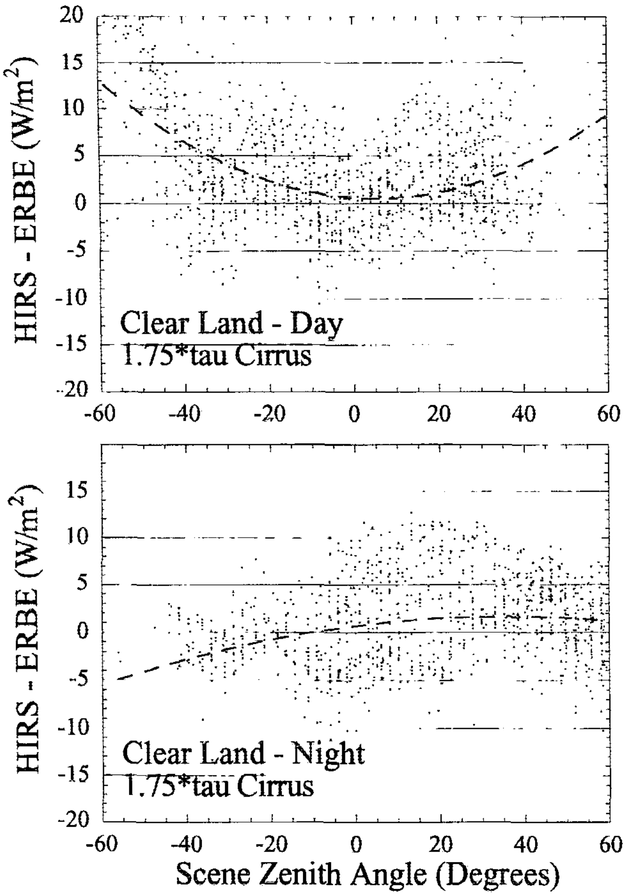

FIG. 11. As in Fig. 9 but for clear land scenes.

as shown by Gruber et al. (1990), and it yields excellent comparisons relative to ERBE. The long series of HIRS data could be used to produce a more accurate time series of the global longwave budget than the one obtained from the AVHRR. Since the HIRS will be used operationally through the launch of the next dedicated radiation budget instrument, it offers the best possibility of obtaining an ongoing, accurate, long-term series of the global distribution of outgoing longwave radiation. NOAA/National Environmental Satellite Data and Information Service is planning to implement a HIRS OLR model sometime in the 1993–94 time period.

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