Surface Net Solar Radiation Estimated from Satellite Measurements: Comparisons with Tower Observations

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ABSTRACT

A parameterization that relates the reflected solar flux at the top of the atmosphere to the net solar flux at the surface in terms of only the column water vapor amount and the solar zenith angle was tested against surface observations. Net surface fluxes deduced from coincidental collocated satellite-measured radiances and from measurements from towers in Boulder during summer and near Saskatoon in winter have mean differences of about 2 W m^{-2}, regardless of whether the sky is clear or cloudy. Furthermore, comparisons between the net fluxes deduced from the parameterization and from surface measurements showed equally good agreement

daily means, respectively. The standard error for the hourly means ranges from about 7% to 50% with a median value larger than 20%. In most cases, as stated by Schmetz, the reported uncertainty may be underestimated, since most of the techniques have been tuned on the basis of preliminary comparisons. An independent examination of four selected algorithms has been carried out recently by Charlock and Whitlock (WCRP-69 1992) using datasets from the International Satellite Cloud Climatology Project (ISCCP) and the Global Energy Balance Archive (GEBA) (Ohmura and Gilgen 1991). The comparisons of monthly mean values found that two of the methods gave 25 W m^{-2} rms error, while the other two gave rms errors larger than 50 W m^{-2}. Considering that there is also error in the estimation of surface albedo, the uncertainty in the retrieval of surface net solar radiation by this approach may be significantly higher than the above values. Ramanathan (WCP-115 1986) and Cess and Vulis (1989) therefore proposed an approach to directly estimate surface net solar radiation. A linear parameterization model can estimate the net surface solar radiation quite accurately for clear skies when compared with collocated tower observations (Cess et al. 1991). Moderate systematic errors were, however, found when this clear-sky algorithm was applied to cloudy skies (Cess et al. 1993).

A new algorithm was described by Li et al. (1993) that relates the net solar radiation at the surface to the reflected solar flux at the top of the atmosphere (TOA). This parameterization, which is based solely on radiative transfer calculations, makes use of two parameters, the solar zenith angle and the column water vapor amount. No information on the nature of the surface or cloud optical thickness is required. Although slightly different parameterizations were developed for different cloud types, we will show below that differentiation according to cloud type is unnecessary and a single parameterization that is independent of cloud type is adequate for determining the net surface solar radiation. Results from the application of a single parameterization to about 70 different combinations of cloud type, cloud optical thickness, surface type, water vapor amount, and haze amount agreed with results from detailed radiative transfer calculations to within 10 W m^{-2} for more than 90% of the cases (Li et al. 1993). Compared with previous models, the new parameterization provides a simple way of obtaining the global climatology of the surface solar radiation budget from satellite measurements (Li and Leighton 1993).

The purpose of the present paper is to demonstrate that the parameterization of Li et al. (1993) reproduces well measurements of the net surface solar radiation. The outgoing flux at the TOA is obtained from instantaneous measurements by the broadband scanning radiometer on the *Earth Radiation Budget Satellite* (*ERBS*). The surface fluxes deduced from application of the parameterization to the TOA fluxes are compared with measurements of the net surface solar radiation from upward- and downward-facing pyranometers mounted on instrumented towers.

2. Data

The satellite data used in this study are from the Earth Radiation Budget Experiment (ERBE), which provides calibrated broadband measurements of both shortwave and longwave outgoing irradiance (Barkstrom and Smith 1986). It consists of three satellites, *NOAA 9, NOAA 10*, and *ERBS*. The two NOAA spacecraft are in sun-synchronous polar orbits. *ERBS* has an orbit inclined 57° relative to the equator, which allows observations at different local times. The nadir footprint of the *ERBS* scanner is roughly 35 km in diameter. Data are selected from *ERBS* that match up spatially and temporally with surface observations.

In order to match the large field of view of the satellite radiometer as well as possible, solar radiation measurements made from two instrumented towers were utilized, the 300-m Boulder Atmospheric Observatory (BAO) tower, and a 10-m tower near Saskatoon, Saskatchewan, that is operated by the Canadian Atmospheric Environment Service.

The BAO tower is located at 40.048°N, 105.008°W, and is surrounded by dry agricultural plains. The pyranometers mounted at the top of the tower were calibrated at the NOAA Solar Radiation Facility. The uncertainty in the measurements is better than the larger of 2% or 7 W m^{-2} (Cess et al. 1991). Measurements were sampled every five seconds but processed as one-hour averages. The tower measurements used in the present work are from the period April–September 1986 and July 1987. There are a total of 239 pairs of collocated *ERBS* and tower measurements, 120 collected in the morning and 119 in the afternoon. According to the ERBE scene identification algorithm, 54 are identified as being for clear skies and the remaining 185 as being for cloudy skies. The distribution of the observations between the seven months is given in Table 1. The data are identical to those used by Cess et al. (1993) for a similar purpose and the collocation procedure has been described in detail by Cess et al. (1991). As in Cess et al. (1993), the correction to the hourly averaged tower data that was applied by Cess et al. (1991) to temporally collocate the satellite and tower data was not carried out, because this procedure applies only for clear skies. Precipitable water amounts were obtained from the Denver National Weather Service radiosonde data.

The Saskatoon tower is located at 52.14°N, 107.07°W, and is surrounded by flat agricultural land and some trees, which cover less than 10% of the area within 20 km of the tower. The upwelling and downwelling shortwave irradiances are measured by leveled, ventilated, downfacing and upfacing hemispheric field-of-view Eppley pyranometers. The pyranometers are

TABLE 1. Summary of the number of pairs of tower and collocated *ERBS* measurements.

Month	Clear	Total
	BAO tower	
Apr86	2	26
May86	11	50
Jun86	1	15
Jul86	9	47
Aug86	1	16
Sep86	10	40
Jul87	20	45
Total	54	239
	Saskatoon tower	
Nov89	0	14
Dec89	2	26
Jan90	0	3
Feb90	4	56
Total	6	99

mounted at the top of the tower at the end of a 2-m boom. The pyranometers are calibrated relative to an active-cavity radiometer, the calibration of which can be traced to the WMO standard. The uncertainties due to calibration error, temperature response, and cosine response error are less than 4% for the downward-facing instrument and 6% for the upward-facing instrument. Data are collected at the rate of six measurements per minute and are recorded as one-minute averages.

Radiation observations at the Saskatoon tower started in November 1989, thus providing only four months of overlap with the *ERBS* scanning radiometer data before its failure on 28 February 1990. Because of the low height of the tower (10 m), the field of view of the downward-facing pyranometer is much smaller than the *ERBS* radiometer pixel size, and therefore there is the potential that the surface type seen by the radiometer on the satellite might be different from the surface type seen by the radiometer on the tower. To minimize these differences, comparisons with measurements from the Saskatoon tower are only made when the surface is snow covered. Snow cover in the Boulder area, by contrast, is uneven and produces surfaces for which the surface albedo is very inhomogeneous. For this reason, winter data at Boulder were not analyzed. Within the four months when both the Saskatoon tower and *ERBS* provided data, there were a total of 99 pairs of observations that satisfied these conditions (Table 1). In view of the uncertainty of the ERBE scene identification over snow/ice (Li and Leighton 1991), sky conditions are determined from the surface hourly weather observations. On the basis of these observations, 6 of the 99 data pairs are found to be for clear skies, that is cloud amount is equal to zero. Precipitable water amounts were computed from the radiosonde observations collected at The Pas, Manitoba, about 400 km to the east.

3. Algorithm

A detailed description and discussion of the algorithm is given in Li et al. (1993), but for completeness a brief description is given here. The fraction of the irradiance incident at the top of the atmosphere that is absorbed at the surface, a_s, is related to the local planetary albedo, r, by

$$a_s = \alpha(\mu, p) - \beta(\mu, p)r \tag{1}$$

where μ is the cosine of solar zenith angle and p is the precipitable water in centimeters. The slope β is expressed as

$$\beta(\mu, p) = \beta_0(\mu) + \Delta\beta(p) \tag{2}$$

with

$$\beta_0(\mu) = 1 + A + B\ln(\mu) \tag{3}$$

and

$$\Delta\beta(p) = -0.0273 + 0.0216\sqrt{p}. \tag{4}$$

Similarly, the intercept α may be expressed in the form

$$\alpha(\mu, p) = \alpha_0(\mu) + \Delta\alpha(\mu, p), \tag{5}$$

where

$$\alpha_0(\mu) = 1 - \frac{C}{\mu} - \frac{D}{\sqrt{\mu}}, \tag{6}$$

and

$$\Delta\alpha(\mu, p) = \frac{1}{\mu}[1 - \exp(-\mu)](0.0699 - 0.0683\sqrt{p}). \tag{7}$$

Different sets of values of the coefficients A, B, C, and D were determined for clear skies and different cloud types (Li et al. 1993). As will be shown, however, application of the clear algorithm ($A = 0.0815$, $B = 0.0139$, $C = -0.01124$, and $D = 0.1487$) to all data, regardless of cloud cover or cloud type, gives results that are as good as the results obtained when the algorithm is applied to clear-sky data only. Therefore, only the clear-sky algorithm is used here.

4. Comparison of satellite and surface measurements

The solid points in Fig. 1 compare the net solar fluxes measured near the surface from the BAO tower with the fluxes determined from the parameterization applied to the *ERBS* TOA fluxes and precipitable water from the Denver radiosonde for the 54 clear-sky cases. There is some significant scatter about the line corresponding to perfect agreement, the standard deviation being 35 W m^{-2}, or 5.9%. As discussed by Cess et al. (1993), part of this scatter is present because the tower measurements are averaged over an hour; thus, depending upon when within the hour the satellite has passed overhead, there will be a difference between the average value of μ during the tower measurement and the value of μ when the satellite measurement was

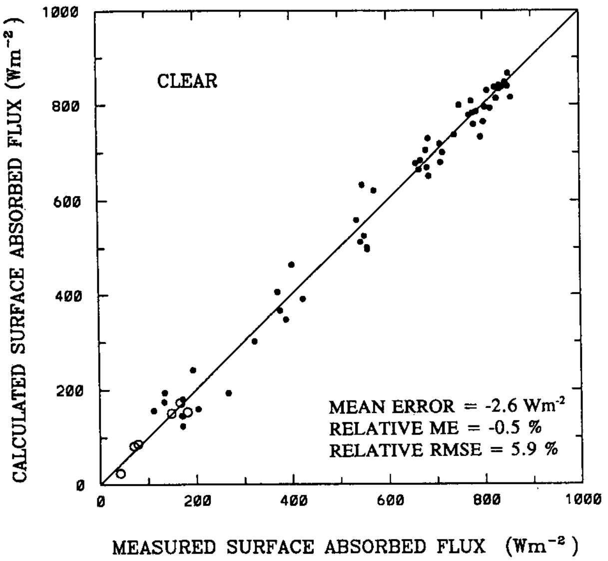

FIG. 1. Comparison of the net flux measured at the BAO tower (solid points) and Saskatoon tower (open circles) with the net flux determined from ERBS measurements for clear skies.

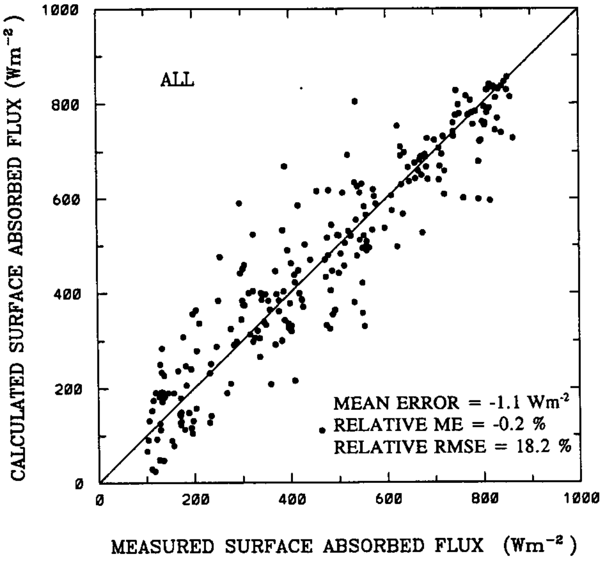

FIG. 2. Comparison of the net flux measured at the BAO tower with the net flux determined from ERBS measurements for clear and cloudy skies.

taken. This temporal mismatch of the satellite and tower data should produce random differences. More significant than the scatter is the fact that the mean error is very small (-2.5 W m^{-2}), corresponding to a relative error of -0.5%. The implication is that although a single estimate of the net surface solar radiation may differ appreciably from the surface measurement, the difference in the averages of a large number of measurements should be small.

Figure 2 shows a comparison of the net surface fluxes deduced from the satellite measurements and those measured at the surface without regard to cloud cover. The surface fluxes are determined by applying exactly the same algorithm with the same coefficients as were used for the clear-sky retrievals. The error in the mean flux at the surface from the 239 observations is -1.1 W m^{-2}. While this is even slightly less than that for clear-sky cases, the scatter is, however, much larger, with the standard deviation being 85 W m^{-2} or 18.2%. This is understandable since the different fields of view of the radiometers on the satellite and on the tower, and the averaging of the tower data over one-hour intervals, will be much more significant for inhomogeneous cloudy scenes than for clear scenes, especially when the cloud is broken. Depending on the amount and spatial distribution of cloud, the location of the satellite pixel relative to the tower may introduce significant collocation error in addition to temporal match-up error. Inadequacies of the parameterization also contribute to the scatter. To the extent that all of these errors are random, they will become less significant if the data are temporally averaged. The fact that the mean error is small suggests that these errors are random.

To determine whether biases exist in the morning data (which are more influenced by low-level cloud), that may cancel opposite biases in the afternoon data (which are influenced predominantly by high-level cloud), the derived and measured fluxes for morning and afternoon observations are compared separately (Figs. 3 and 4). The absence of any significant difference in the mean between the retrievals suggests that determination of the mean net flux at the surface is not very sensitive either to cloud type or height. However, the afternoon data do show larger scatter, the

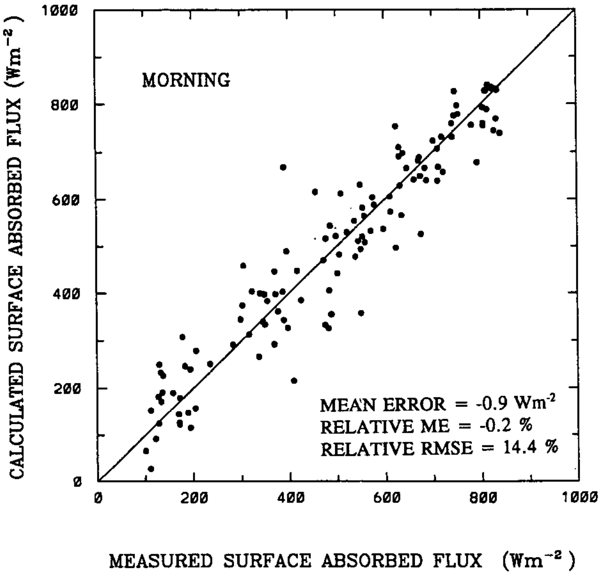

FIG. 3. As Fig. 2 but for morning measurements only.

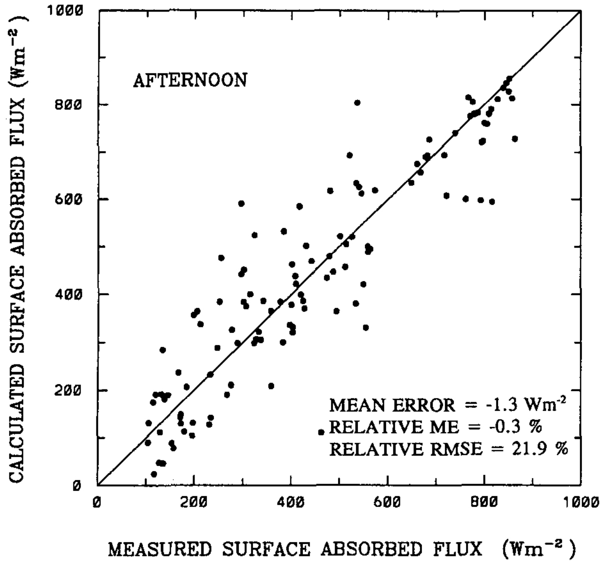

FIG. 4. As Fig. 2 but for afternoon measurements only.

relative random errors in the morning and afternoon being 14.4% and 21.9%, respectively. Presumably this is because of the more frequent occurrence of convective clouds in the afternoon.

Since differences between the satellite and the surface measurements due to spatial and temporal mismatching are random, they should be reduced by averaging. This is clearly illustrated in Fig. 5, which shows the comparison of the mean surface absorbed fluxes observed at the BAO tower and those estimated from the satellite data for each month. The number of observations within one month varies from 15 to 46 (Table 1). Monthly mean water vapor amounts have been used to determine the net surface flux from the satellite-measured fluxes. The resulting values are not to be interpreted as monthly mean fluxes because of nonuniform diurnal sampling. Nevertheless, the good agreement between the values of the averages for each month determined from the parameterization and from the tower measurements demonstrates the promise of the parameterization for determining monthly mean fluxes. The standard deviation in the averaged data is reduced from 18.2% (Fig. 2) to 4.2% (Fig. 5). The randomness of the differences in the measured and derived surface fluxes will assure good accuracy in estimates of long-term mean surface-absorbed fluxes. Li and Leighton (1993), for example, retrieved the global climatology of surface absorbed flux from five years of the ERBE regional data. The construction of the ERBE S-4 dataset involves substantial averaging over an area of 2.5 × 2.5 degrees for each month. It is thus reasonable to expect that the uncertainty in the global climatology of the surface solar radiation budget retrieved from ERBE may fall well within the 10 W m^{-2} that is suggested for climate studies by Suttles and Ohring (WCP-115 1986). It should be emphasized that the large standard error in the unaveraged data cannot be construed as a weakness of the algorithm. Because of different fields of view and different temporal averaging, the radiometers mounted on the tower and on the satellite measure fluxes from quite different scenes. The difference will be greatest when broken clouds are present. The error that may be expected in the determination of the net flux, averaged over the satellite field of view from a single satellite measurement, is substantially less than the standard error resulting from the comparison of the satellite-derived and surface-measured net fluxes.

The Saskatoon tower data provide an additional test of the parameterization for a quite different surface type, namely, snow (Fig. 6). Because of the large distance (400 km) between the tower and the upper-air station at The Pas, Manitoba, only monthly mean values of column water vapor amount were used in the parameterization. Undoubtedly, the differences between the instantaneous column water vapor amounts at Saskatoon and the monthly mean amounts at The Pas will introduce errors in the deduced surface fluxes. Sensitivity tests by Li et al. (1993) show, however, that the surface net solar radiation is not very sensitive to the water vapor amount. Since Saskatoon and The Pas have similar climates, the resulting errors in the surface radiation may not be very significant. As with the Boulder data, there is an appreciable scatter of the points about the line corresponding to perfect agreement, the standard deviation being 33 W m^{-2}, but the mean error is only −0.4 W m^{-2}. Part of the scatter will be due to the use of incorrect values of the column water vapor amount as described above, and part will also be due to the different effects of broken and in-

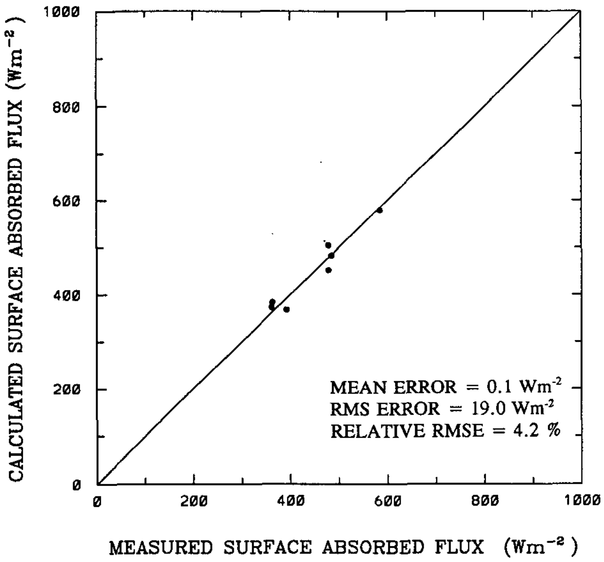

FIG. 5. Comparison of the averages of the net fluxes measured at the BAO tower in each of six months with the average fluxes determined from *ERBS* measurements.

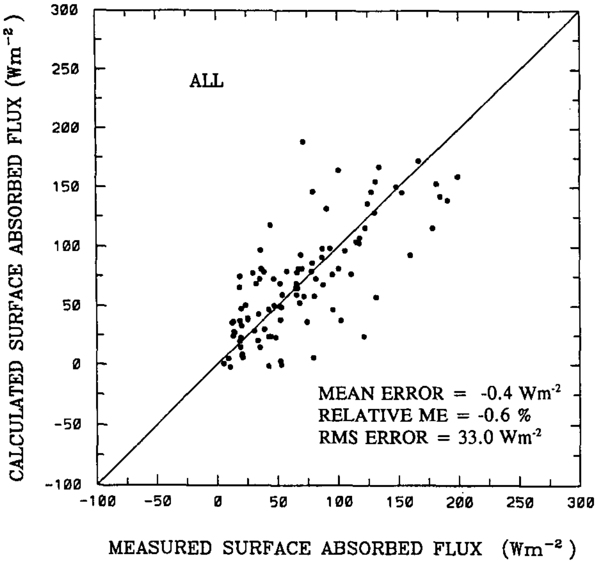

FIG. 6. Comparison of the net flux measured at the Saskatoon tower with the net flux determined from *ERBS* measurements for clear and cloudy skies.

homogeneous clouds on the net fluxes measured at the tower and deduced from the satellite measurements. The small bias error for both the Boulder and Saskatoon data suggest, as expected from the earlier computations (Li et al. 1993), that the algorithm is valid for a wide range of surface types.

The rms error of 19 W m^{-2} shown in Fig. 5 is comparable to the typical rms error in the determination of monthly mean surface insolation (Schmetz 1989). Each data point in Fig. 5 represents the average of between only 15 and 50 observations. Averages over the same number of observations that are used to determine the mean monthly insolation would undoubtedly produce an even smaller rms error. It must also be recognized that the contribution of errors due to the mismatching of the scenes viewed by the surface- and satellite-based instruments to the rms error is larger for the retrieval of net solar radiation than for the retrieval of insolation. This is partly due to the fact that in almost all retrievals of insolation, data from operational satellites were used that can have spatial resolution as high as 1 km. Another reason is that spatial variability of net solar radiation is stronger than that of surface insolation because of variability of the surface albedo. Finally, the comparisons shown here are completely independent of the development of the algorithm; that is, the algorithm has not been tuned to any portion of the data.

5. Empirical evaluation of the algorithm sensitivity

a. Surface type

The lack of sensitivity of the algorithm to surface type can be demonstrated clearly by including the Boulder and Saskatoon data for clear skies on the same plot. The open circles in Fig. 1, which represent the Saskatoon clear-sky data, fall on the same line as the Boulder data. Combining the Saskatoon clear-sky data with the Boulder clear-sky data produces a negligible change in the mean error of the calculated net surface flux, from −2.5 W m^{-2} to −2.6 W m^{-2}. It is also noteworthy that the scatter in the Saskatoon data is smaller than the scatter in the Boulder data, presumably due to the better temporal matchup of the Saskatoon data and the more homogeneous snow-covered surface.

b. Cloud amount

The ability of the present parameterization (Li et al. 1993) to account for the influence of clouds on the relationship between the TOA and surface net fluxes may be best appreciated if it is compared with the empirical clear-sky algorithm of Cess et al. (1993). That parameterization is a linear fit to the clear-sky TOA and surface data that does not explicitly account for changes in the solar zenith angle. Figure 7 shows the relative mean differences between the measured net surface radiation and the values deduced from the present parameterization (Li et al. 1993) for both clear- and all-sky data, and from the empirical clear-sky parameterization applied to the all-sky data. Since the empirical clear-sky model is derived from a fit to the clear-sky observations, there is no bias error for the clear data. The present parameterization, which, it must be emphasized, was obtained from theoretical calculations only, gives a negligible error when compared to the clear-sky measurements. Furthermore, the parameterization still has negligible error when applied to all the data, whereas the empirical clear-sky model has an error of −4.4%. This result is in agreement with the theoretical finding of Li et al. (1993) that their

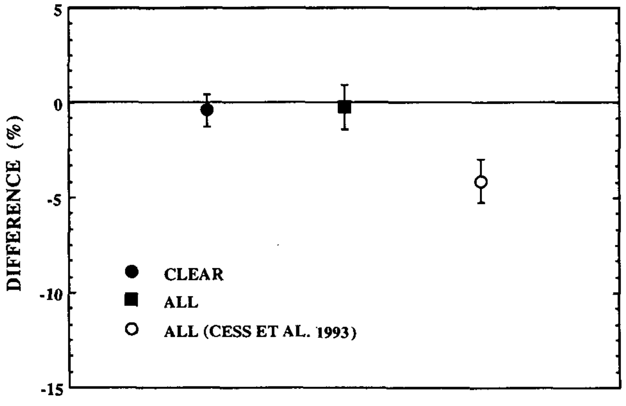

FIG. 7. Relative mean difference between the measured surface net solar radiation and the values estimated from satellite measurements for clear-sky and all-sky data. Solid and open points correspond to the clear algorithm of Li et al. (1993) and Cess et al. (1993), respectively. The vertical bars denote the standard error in the mean differences.

parameterization is virtually independent of cloud amount.

Figure 8 shows the surface insolation as a function of the cosine of the solar zenith angle for the observations from the Boulder tower for which the ERBE scene identification algorithm indicated that the scene was not clear. The straight line is a fit to the 54 observations for which the ERBE scene identification showed clear skies. Deviations of the points from the straight line are basically indications of the impact of clouds on the surface insolation. It is evident that the observations include scenes with a variety of cloud amounts and optical thicknesses, which have a substantial influence on the surface insolation and thus on the surface net solar radiation. In contrast with previous studies, the present algorithm is able to take into account the effect of cloud optical thickness and cloud amount without incorporating any cloud information.

c. Cloud type

Cess et al. (1993) showed that their empirical clear-sky algorithm produces a slightly larger error when it is applied to the afternoon Boulder measurements, compared to the error from morning measurements. It is likely that the cause of the difference is the prevalence of different cloud types in the morning and afternoon. That the present parameterization does, in fact, implicitly account for both cloud amount and type is convincingly demonstrated by subdividing, as did Cess et al. (1993), the Boulder data into morning and afternoon measurements. Figure 9 shows the mean differences between the measured and deduced surface fluxes for the Boulder tower dataset for the two parameterizations, for all the data, and for the data grouped into morning and afternoon observations. As discussed above, the clear-sky parameterization of Cess et al. (1993) shows a larger error for the afternoon observations. The present parameterization, on the other hand, shows no significant difference in the morning and afternoon results. The apparent lack of influence of cloud type is demonstrated even more strongly by subdividing the data into early morning (before 1000 LT), midday (from 1000 to 1400 LT), and late afternoon (after 1400 LT) observations (Fig. 10). The late afternoon results from the parameterization of Cess et al. (1993) show an error of 8.3%, most probably as a result of the influence of high cloud. The new algorithm shows little trend in the magnitude of the error throughout the day, and in fact the difference between the measured and deduced net fluxes are negligible for each group of data.

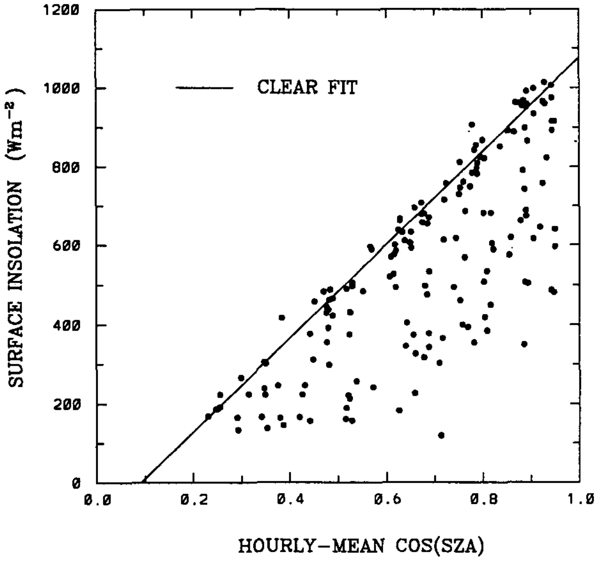

FIG. 8. BAO tower measurements of surface insolation as a function of the hourly mean of the cosine of the solar zenith angle for the 185 cloudy (i.e., 239 total minus 54 clear) measurements (taken from Cess et al. 1993). The straight line represents the least-square regression to the BAO clear-sky points.

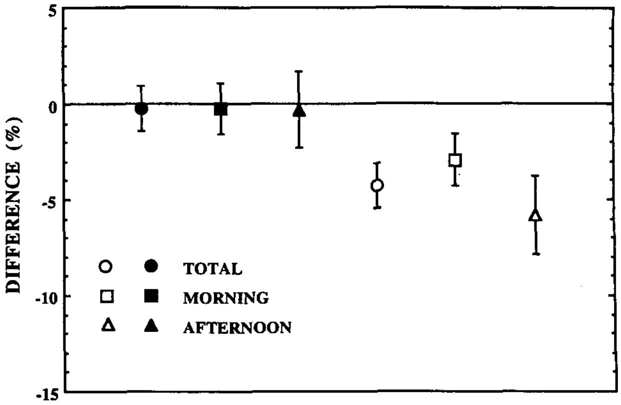

FIG. 9. As in Fig. 7 but for all morning and afternoon measurements.

d. Spatial and temporal averaging

To retrieve large-scale surface solar radiation budgets from satellite observations, it is necessary to use spa-

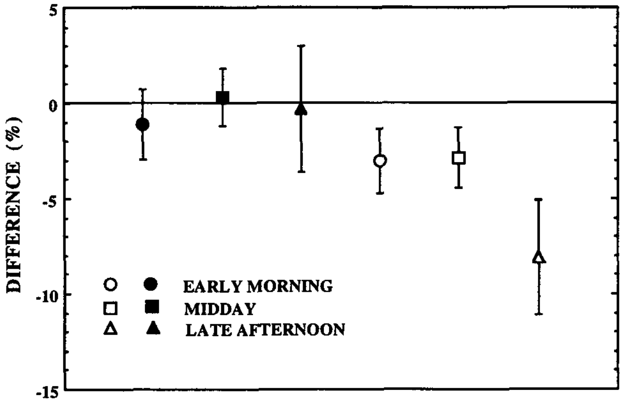

FIG. 10. As in Fig. 7 but for early morning, midday, and late afternoon measurements.

tially and temporally averaged observations. It is thus necessary to show that the parameterization of Li et al. (1993) may be applied to averaged data as was done in Li and Leighton (1993). The quantities that appear in the parameterization and must be averaged are the upwelling TOA flux, the precipitable water, and the cosine of the solar zenith angle.

Because the parameterization (1) is linear in the local planetary albedo, or equivalently in the TOA upwelling irradiance, spatially averaging the satellite-measured irradiances over many pixels will not introduce any error in the retrieval of the average net solar radiation at the surface.

To test the influence of using average water vapor amounts instead of the values obtained from individual soundings, the surface radiation budgets for Boulder were recalculated with monthly mean values of precipitable water. This recalculation produced a change in the mean difference between the measured and calculated surface net fluxes from -1.1 W m^{-2} to -3.26 W m^{-2}, the relative error changing from -0.2% to -0.56%. The monthly mean values of precipitable water ranged from 0.75 cm in April 1986 to 1.77 cm in July 1986, and the standard deviations of the daily water vapor values for these two months are 0.25 and 0.44 cm, respectively. It is possible that using monthly mean water vapor amounts for locations where the variability in precipitable water is much greater will introduce larger errors.

In spite of the apparently complicated dependence of the parameterization on μ in (3), (6), and (7), the dependence is, to a good approximation, reasonably linear (Li et al. 1993). Thus, using mean values of μ and p in the parameterization only increased the mean error from -3.26 W m^{-2} to -5.77 W m^{-2}, and the relative error from -0.56% to -0.99%.

These results suggest that it should be quite acceptable to use average quantities in the parameterization to obtain global distributions of net surface solar radiation.

6. Concluding remarks

Measurements from space are the only way of obtaining global and continuous information about the surface solar radiation budget. There are several steps in the transformation of satellite measurement to the surface solar radiation budget, each of which will introduce errors. These include the absolute measurement of the broadband radiance at the satellite and the accompanying calibration uncertainty, the conversion of radiance to irradiance by means of bidirectional models that are scene dependent, and the transformation of outgoing irradiance at the top of the atmosphere to net flux at the surface, which depends on absorption and scattering in the atmosphere. It is this last step that was addressed by Li et al. (1993), who derived a new parameterization of the net surface flux in terms of the net flux at the top of the atmosphere, the column water vapor amount, and the cosine of solar zenith angle. The algorithm requires no information about the nature of the surface nor about the absence or presence of clouds. The parameterization was deduced exclusively from radiative transfer calculations and is entirely independent of surface observations. Although it appeared to be promising as well as simple, there could be little confidence in its application without testing it against observations.

In the present study, the net fluxes at the surface determined from two sets of tower measurements are compared with fluxes deduced from broadband radiance measurements from *ERBS* by application of the Li et al. (1993) parameterization. Thus, errors in each of the three steps mentioned above may introduce differences between the measured and calculated fluxes. Furthermore, the fields of view of the satellite radiometer and the downward-facing pyranometers on the towers are quite different, especially for the pyranometer on the Saskatoon tower. It is, therefore, quite remarkable that there should be so little systematic difference between the measured fluxes and the fluxes deduced from the parameterization. The small bias error suggests that the errors in net fluxes that have been averaged temporally and/or spatially over many independent measurements, as would be the case for climate studies, will be very small.

The algorithm appears to be insensitive to cloud type. Partitioning of the Boulder data into early morning, midday, and late afternoon observations produced equally good agreement between the deduced and measured fluxes for each subset of the data. This is in contrast to the results obtained using the Cess et al. (1993) clear-sky parameterization, which gave significantly poorer agreement for the afternoon measurements than for the morning measurements, presumably because of the predominance of different cloud types in the morning and afternoon.

Although the parameterization algorithm has only been validated against two sets of tower measurements, they represent two quite different surface types and different seasons. The Boulder tower dataset included values of net fluxes greater than 800 W m^{-2} whereas the Saskatoon data included net fluxes as small as 5 W m^{-2}. Thus, the measurements represent substantially different conditions. The results provide considerable confidence that the parameterization may be used to convert top-of-the-atmosphere solar fluxes to net surface fluxes for climate studies.

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