Relationships between Measured and Satellite-Estimated Solar Irradiance in Texas

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ABSTRACT

The accuracy of satellite-estimated surface solar irradiance and the relationship between irradiance at pairs of locations and distance between the pairs were examined. Daily measured and satellite-estimated irradiances were available for a 2–3 year period from 20 Texas locations. For the distance analysis, irradiances were normalized as a percentage of daily potential surface irradiance.

In comparing the measured and satellite-estimated irradiances, the bias (the mean of satellite-estimated minus measured irradiance differences for the period of record) increased from ±1 MJ m⁻² d⁻¹ in the northern two-thirds of Texas to 2 MJ m⁻² d⁻¹ in the southern portion. The root-mean-square errors (RMSEs) between irradiances averaged 2.5 MJ m⁻² d⁻¹, which is 12% of the mean annual statewide potential surface-irradiance. Errors were at a maximum in the winter and a minimum in the summer.

Between measured irradiances at pairs of locations, RMSEs increased rapidly for the first 200 km distance between the pairs and increased at a lesser rate thereafter. Errors were reduced for five-day averages. Correlations of normalized measured or satellite-estimated irradiances between pairs of locations decreased exponentially as a function of the distance between the pairs. This decrease was less for five-day averages than for daily values. The correlation decrease as a function of distance was greater in this study than those previously reported and was likely the result of normalization.

These results are relevant to individuals interested in the accuracy of satellite-estimated irradiances, as well as those interested in interpolating measured irradiances from an existing network, or establishing an irradiance measurement network.

1. Introduction

For both agricultural and energy planning purposes, information on surface solar irradiance is critical. However, surface solar irradiance is one of the least-measured meteorological elements and, therefore, it is often estimated by interpolation from measurements at other locations or from satellite or other surrogate data.

Using regression techniques, Tarpley (1979) developed an algorithm for estimating surface solar irradiance from geostationary satellite data. Standard errors of daily satellite-estimated irradiances for an independent data set were less than 10% of the mean, but measured irradiances under cloudy conditions were generally overestimated. Raphael and Hay (1984) evaluated the performance of the Tarpley algorithm in British Columbia. They altered some of the coefficients to increase model predictive capability. These locally derived coefficients did not improve model performance for partly cloudy and overcast conditions. As the averaging period increased (in this case from hours to days), errors decreased. They found daily errors of approximately 12% of the mean for the 48 days for which they tested the model. Sullivan et al. (1984) compared measured and satellite-estimated irradiances, using the Tarpley algorithm, from March through September 1983 for various locations in the United States. Most locations showed closer agreement between the irradiances in the early months with agreement deteriorating thereafter. The bias was approximately 0.8 MJ m⁻² d⁻¹ and root-mean-square errors (RMSEs) were approximately twice this. Again, weekly averages were more accurate than daily values.

The relationship between the irradiance correlation at a pair of locations and the distance between the pair has been evaluated for different regions. For the eastern United States, Atwater and Ball (1978) used 28 pairs of locations where irradiance was measured varying over distances of from less than 100 to nearly 2400 km. Suckling and Hay (1976) conducted a similar study using locations in western Canada, with distances varying from 55–1180 km. In both of these studies, the relationship between irradiance correlation and distance was exponential. For their analysis, Kerr et al. (1968) used data from a mesoscale network in Wisconsin for the period December 1966–June 1967. Solar irradiance at any point in the network could be estimated with an approximate standard error of ±25% or less of clear sky irradiance on a daily basis, and ±10% on a monthly basis. Baker and Skaggs (1984) evaluated the relationship between distance

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and the correlation between solar irradiance and sunshine measurements. They found this relationship to be linear from 60–550 km.

It is the objective of this study to evaluate 1) the accuracy of daily satellite-estimated surface solar irradiances, and 2) the relationship between the correlation of daily measured or satellite-estimated irradiance at pairs of locations and the distance between the pairs for 20 Texas locations.

2. Data

Measured daily surface solar irradiances were available from weather stations at 20 locations in Texas (Table 1) established in conjunction with an Agricultural Weather Advisory Program (Dugas et al., 1984). Weather station details have been presented by Dugas and Whitis (1984). Irradiance measurements were made using Li-Cor pyranometers. Sensors come from the factory with a calibration uncertainty of ±5%. Pyranometers were calibrated after receipt from the factory by checking against a local standard. Sensors were recalibrated in the field in the same manner in October 1983. No sensors were found to be out of calibration by more than ±5%.

Locations were arbitrarily divided into three groups: northern (Table 1, location numbers 1–11), central (numbers 12–16), and southern (numbers 17–20). The period of record for the central locations, except Dallas, is 11 July 1981–31 December 1983. The period of record for others is 1 April 1982–31 December 1983.

Daily satellite-estimated irradiances (after Tarpley, 1979) were obtained from data files stored on the National Oceanic and Atmospheric Administration central computer facility. Estimates for a 1° latitude by 1° latitude area were available for the period of record for which measurements had been made and were rounded to ±0.21 MJ m⁻² d⁻¹. At these latitudes, the size of these areas is approximately 110 × 90 km. Until June 1982, five satellite images were accessed for each daily estimate; seven images were used subsequently. The irradiance estimate for the area centroid (i.e., the intersection of latitude and longitude lines) which was closest to the location where irradiance was measured was used as the satellite-estimated value for that location (Table 1 and Fig. 1). For example, for location number 2 (Silverton), whose coordinates are 34.4°N, 101.3°W, the estimate for the centroid at 34°N, 101°W was used.

3. Methods

Daily measured or satellite-estimated irradiances that were missing were not estimated by interpolation or other means, and were not used in the analyses. To evaluate satellite-estimated irradiance accuracy, daily measured and estimated irradiances were compared with each other for the entire period of record and for each month. Statistics such as the bias and RMSE were calculated.

For the distance and irradiance analysis, irradiances were normalized as a percentage of potential surface irradiance for that day. Potential surface irradiance was calculated as the product of potential irradiance at the top of the atmosphere (assuming a solar constant of 1353 W m⁻²) and an atmospheric transmittance. The transmittance varied a few percent throughout the year and was assumed to be a constant for the year. It was computed for each station as the fraction of the subjectively determined, daily clear-sky irradiance and daily potential irradiance at the top of the atmosphere. For measured and satellite-estimated irradiances, correlation/regression analyses were conducted for all data and by months to determine the relationship between irradiance at a pair of locations and the distance between the pair.

4. Results and discussion

a. Satellite-estimated and measured irradiance comparisons

Statistics from the comparison of daily measured and satellite-estimated surface irradiances are shown in Table 2. The bias (the mean of satellite-estimated minus measured irradiance) was near zero for northern, slightly negative for central, and highly positive for southern locations. These geographical differences are a result of the nature of the climatological, especially cloud, regimes which exist in the three areas and the different periods of record. The negative biases at the central locations are primarily the result
of two months in 1981 with very large negative biases. The large positive biases at the southern locations may be a result of the cloud patterns in this coastal environment. Cloudiness at Corpus Christi (on the coast in the center of this region) is generally, and especially in the summer, maximum in the early morning and minimum near midnight (United States Department of Commerce, 1963). Even though satellite images used in the estimating algorithm were typically made from early morning (0800 LST) until early evening (2000 LST), this diurnal cloud pattern may not be fully accounted for in the procedure. This possibility indicates that the procedure may be inadequate for coastal environments; it was originally developed and tested exclusively at continental locations. Differences in mean measured irradiance within a group are primarily a result of different sample sizes.

RMSEs (normalized as a percentage of mean measured irradiance) averaged 16% across locations. Errors ranged between 2 and 3.3 MJ m\(^{-2}\) d\(^{-1}\) and were generally larger for the central and southern stations in both absolute (MJ m\(^{-2}\) d\(^{-1}\)) and relative (%) terms. The larger errors at the central stations are due, in part, to the very poor predictions in August and September 1981 and at the southern stations because of the large bias discussed previously. Given the relatively small range in RMSEs and the resolution of the satellite estimates, one cannot likely detect if there is a relationship between error and the distance between the location where irradiance was measured and the centroid location. RMSE differences among regions are greater than those within a region.

### Table 2. Statistical results between satellite-estimated (SAT) and measured (OBS) solar irradiance data.

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<tr>
<th>Location number</th>
<th>Location name</th>
<th>Bias* (MJ m(^{-2}) d(^{-1}))</th>
<th>Bias (MJ m(^{-2}) d(^{-1}))</th>
<th>RMSE** (MJ m(^{-2}) d(^{-1}))</th>
<th>OBS (MJ m(^{-2}) d(^{-1}))</th>
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<th>RMSE (%)</th>
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* Mean value of SAT minus OBS values for period of record.
** Root-mean-square error.
† Potential daily surface solar irradiance.
‡ OBS = f(SAT).
Results from regressing measured irradiance as a function of satellite-estimated irradiance showed that in all cases but one, Dallas, the slope was less than 1.0; except at station 17 (Luedke), the intercept was greater than zero (Table 2). Slopes and intercepts were lower at the southern locations. Satellite-estimated irradiances were 5–10% greater than measurements. Examples of measured and estimated irradiances are shown in Fig. 2. For Dallas the points were close to the 1:1 line and there was no obvious trend in the degree to which estimates were greater or less than measurements at low or high irradiances. The data for Banquette showed a consistent overestimate of irradiance using the satellite estimates.

The data were also analyzed to determine if there were any monthly patterns. Monthly values of the RMSE (normalized as a percentage of potential) for Aquilla showed that maximum percentage errors occurred during the winter (Fig. 3). This is a result of a reduced potential and a 1–2 MJ m\(^{-2}\) d\(^{-1}\) larger RMSE in the winter (not shown). Late spring, summer, and early fall errors were consistently less than 10% of potential. Other stations showed a similar pattern.

**Fig. 2.** Measured and satellite-estimated irradiances at Dallas and Banquette.
coefficients based upon data from a different measurement network than was used in the original study. Our data show no significant improvement or degradation in predictive capability following either change.

b. Distance and irradiance correlations

Correlation coefficients were determined between measured irradiances for all pairs of locations and the satellite-estimated irradiances for all pairs of centroids. Irradiances were considered in both absolute terms (MJ m⁻² d⁻¹) and as a percentage of potential surface irradiance. Correlation coefficients were compared with the distance between the pair.

For all of the measured data, an exponential decay of correlation as a function of distance was found (Fig. 5). The data are essentially linear to approximately 500 km. Patterns for January and July (not shown) exhibited more variability because of the reduced sample size. The rate of decrease of irradiance correlation as a function of distance was greater in July than in January or for all of the data. This increased rate was likely a result of the scattered cumulus cloud activity associated with the Texas midsummer climate. The relationship between satellite-estimated irradiance correlation for a pair of centroids and distance between the centroids was similar (Fig. 6).

A similar response to distance can be seen when examining RMSEs between measured irradiances at a pair of locations as a function of the distance between the pair (Fig. 7). A least-square, best-fit line was plotted for the results from these analyses and previous studies. Coefficients of determination for the daily and five-day average data in this study were 86 and 91%, respectively. Errors decreased substantially with a five-day average relative to daily values. Daily errors increased rapidly for the first 200 km and thereafter increased at a lower rate. The slope for
daily values in all studies is very steep from 0–200 km. After 200 km, the lines begin to separate. Even though there may be a statistically significant correlation between irradiances at a pair of locations 200 km apart (i.e., approximately 0.80 from Fig. 5), the RMSE between the two locations may be substantial (i.e., 3.5 MJ m\(^{-2}\) d\(^{-1}\) from Fig. 7) and too large for most applications. This error corresponds to about 15–25% of the average daily irradiance at most Texas locations and is greater than the error from using satellite data to estimate surface irradiance.

The results in this study differ with published material with respect to the decrease in irradiance correlation as a function of distance between a pair of locations. Suckling and Hay (1976) and Atwater and Ball (1978) also showed exponential decays, but the rate of decrease was less than that found in this study (Fig. 8). If measured irradiances in this study were not normalized as a percentage of the potential surface irradiance, the rate of decrease was similar to those previously published. However, upon normalization, the rate of decrease in correlation was much greater. If one does not remove, by normalization, the seasonal pattern of irradiance at midlatitude locations (e.g., the range in mean monthly irradiance at Dallas is approximately 15 MJ m\(^{-2}\) d\(^{-1}\)), the irradiance correlation at a pair of locations would be biased high because of the correlation between the two values which results solely from the seasonal trend.

5. Conclusions

Measured and satellite-estimated daily surface solar irradiances were analyzed to determine 1) the accuracy of satellite estimates and 2) the interrelationships between irradiance at pairs of locations and the distance between the pairs for 20 locations in Texas.

Irradiance errors resulting from use of satellite data in this study were similar in magnitude to those previously published. Large positive biases and slightly larger root-mean-square errors for locations near the Gulf of Mexico were found. No obvious tendency was found for overestimation of irradiance using satellite data at low irradiances. Satellite estimates tended to more consistently overestimate measured irradiances at moderate to high irradiances.

The effect of distance on the irradiance difference between a pair of locations was similar to that previously published; however, the irradiance correlation between stations was lower in this study, possibly due to normalization of the irradiance data. Although it was not possible in this study because of the small longitudinal differences between locations at similar latitudes, it would be interesting to evaluate the azimuthal effect on the relationship between irradiance correlation and distance; i.e., do locations a given distance apart in an east–west direction have a higher correlation than locations the same distance apart in north–south direction.
As Suckling and Hay (1976) reported, an appropriately dense irradiance measurement network for a particular purpose (energy in their case) may not be economically feasible. A similar conclusion could possibly be drawn in all or part of Texas for agricultural and energy applications. Therefore, it is reasonable that further research be conducted to improve and evaluate surface irradiance predictions using satellite and/or other surrogate data. This should be coincident with efforts to expand the measurement network where economically appropriate.

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